SWISS CONTRIBUTION

NANOSPIN

Spin pumping and tuning of magnetization damping by spin Hall currents

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AGH

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

IF PAN

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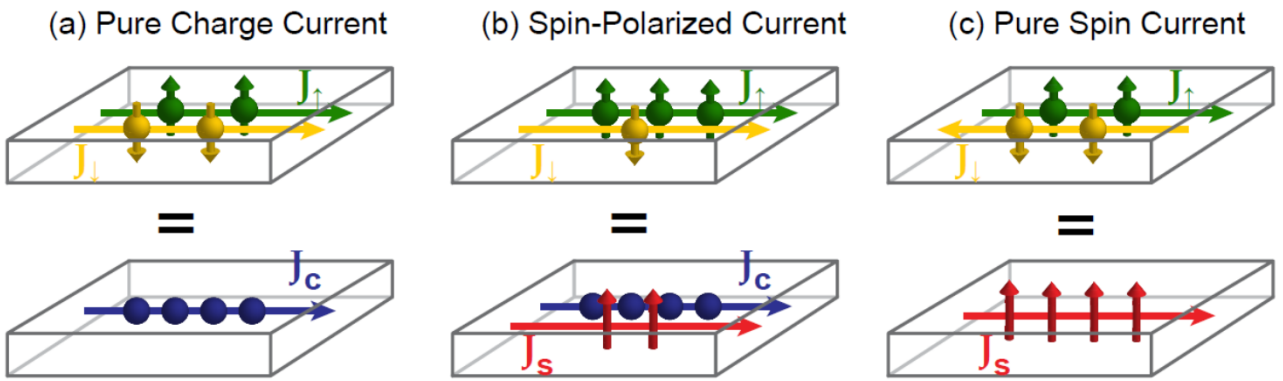
Outline

- Spin currents and spin pumping
- Rashba SO effect on interfaces
- Finemet+Al : $Fe_{66.5}Cu_1Nb_3Si_{13.5}B_9Al_7$
- Ferromagnetic resonance
- Gilbert damping (low damping)
- Capping Pt layer
- FM/NM interface
- Spin Hall effect –DSHE & ISHE

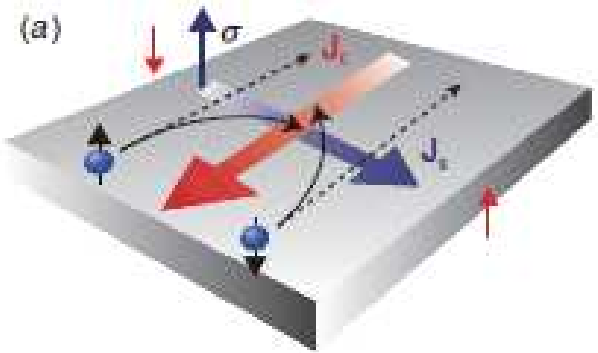
SPIN CURRENT J_S in metallic systems



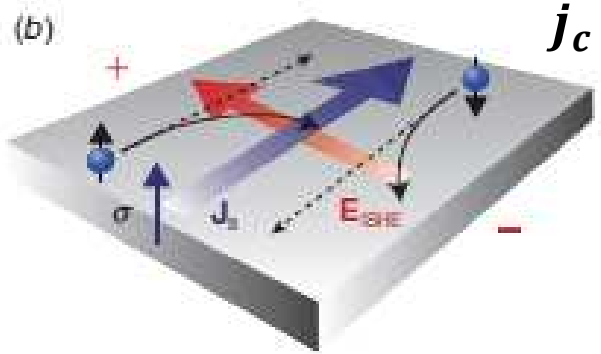
$$\boldsymbol{j_s} = \theta_{SHE}\boldsymbol{j_c} \times \boldsymbol{\sigma}$$

Spin Hall angle

$$\boldsymbol{j_c} = \theta_{SHE}\boldsymbol{j_s} \times \boldsymbol{\sigma}$$

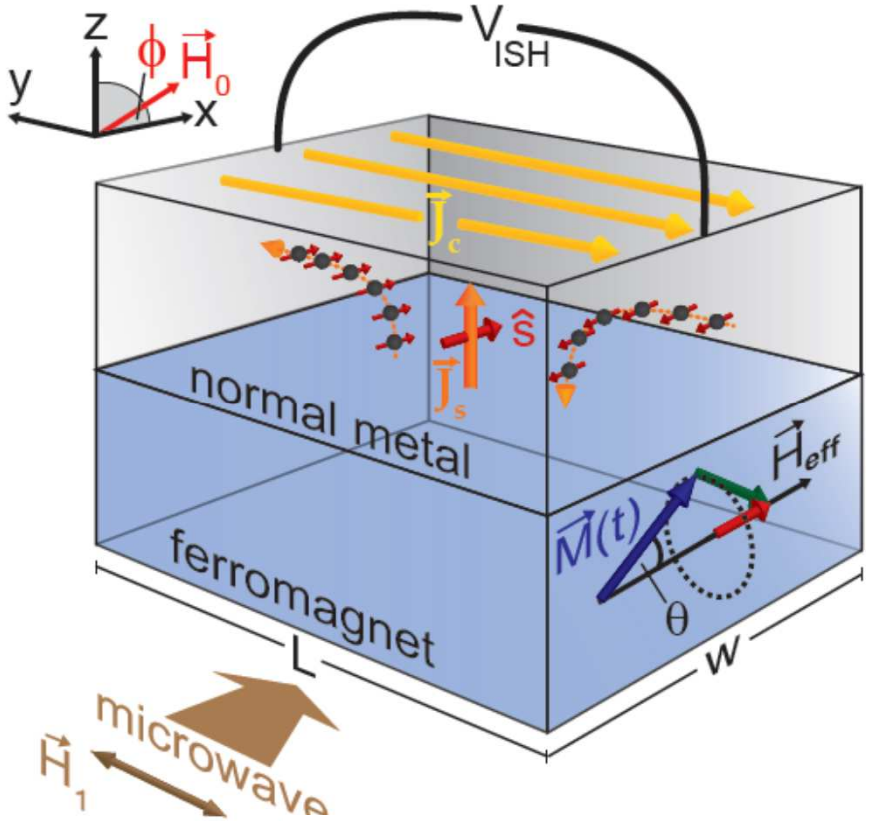


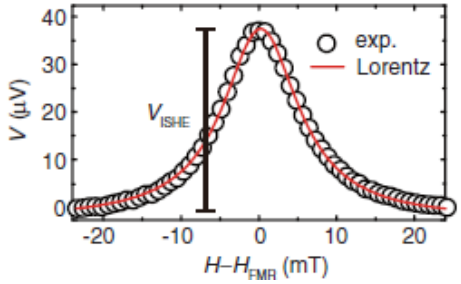
GENERATION of SC (DSHE)



DETECTION of SC (ISHE) Czeschka

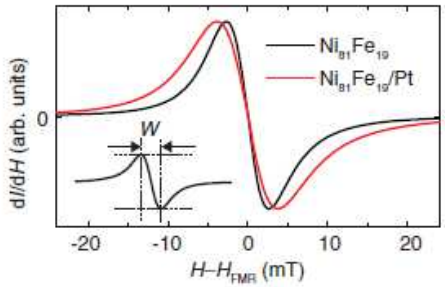
Spin pumping & detection of spin current





? at interface

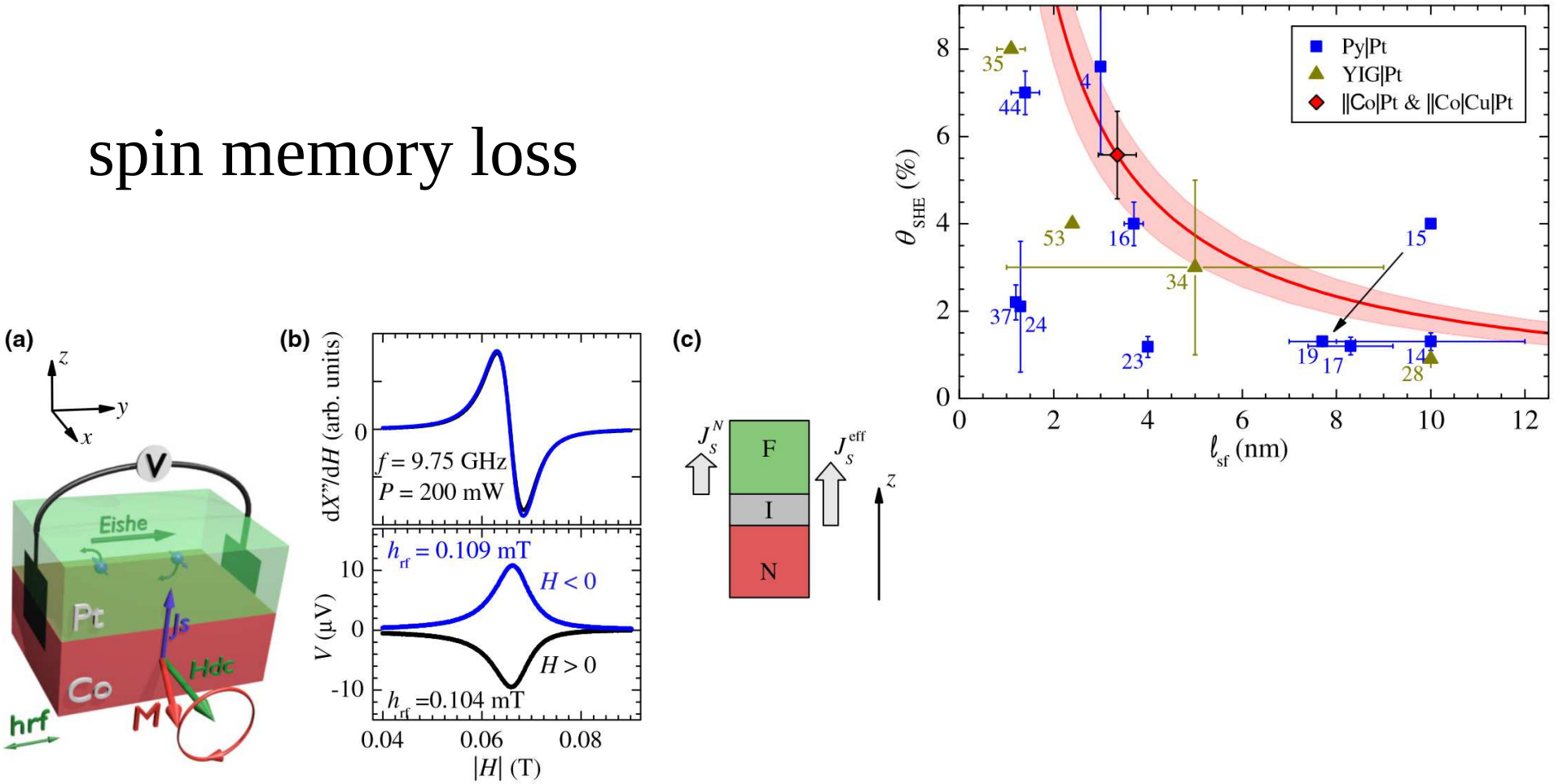
$$\Delta\alpha_{SHE} = \left(\frac{\gamma}{2\pi f M_s V_F}\right) J_s.$$



$$\mathbf{j}^s = \frac{\hbar}{4\pi}\left(g_r \mathbf{m} \times \frac{d\mathbf{m}}{dt} - g_i \frac{d\mathbf{m}}{dt}\right).$$

Spin pumping

spin memory loss

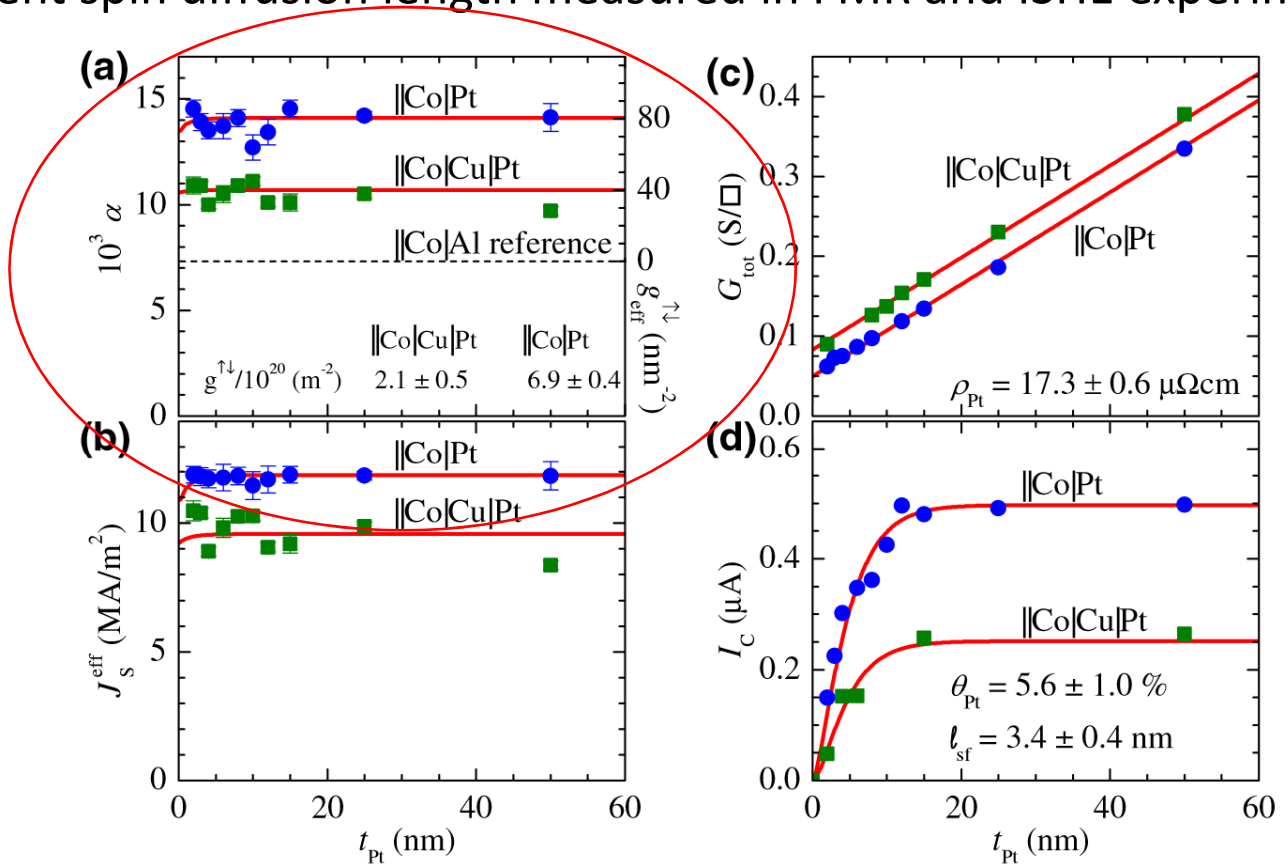


J.-C. Rojas-Sánchez et al., PRL **112**, 106602 (2014)

Spin-memory Loss

Main conclusion:

- spin-memory loss at interface induces a strong spin current depolarization
- different spin diffusion length measured in FMR and ISHE experiment



J.-C. Rojas-Sánchez et al., PRL **112**, 106602 (2014)

SP in the presence of SO coupling

Conventional theory without SO: scattering theory (Tserkovniak)

$$\mathbf{j}^s = \frac{\hbar}{4\pi}\left(g_r \mathbf{m}\times\frac{d\mathbf{m}}{dt} - g_i\frac{d\mathbf{m}}{dt}\right). \qquad g \equiv g_r + ig_i = \sum(1 - r_\uparrow r_\downarrow^*)$$

Conventional theory: ~~influence of disorder at interface~~ ~~influence of SOC~~ (spin-memory loss)

SOC: effect Rashba $V(\mathbf{r}) = \alpha_R \delta(z)(\hat{\mathbf{k}}\times\hat{\mathbf{z}})\cdot\boldsymbol{\sigma}$ Rashba!

$$\mathbf{j}_z(z>0) = \frac{\hbar\Gamma^0}{4\pi}\frac{J_{ex}^2}{J_{ex}^2+\Delta^2}N(z)\mathcal{A}_N\cdot\left(\mathbf{m}\times\frac{d\mathbf{m}}{dt}\right),$$

Γo – SP cond. across interf. without disorder

η – Rashba factor

ξ –back-flow factor

Chen, Zhang PRL 114 (2015)

SP in the presence of SO coupling

(THEORY)

Γ^0 ~ 7 nm^{-2}

α_R ~ 0.03 - 0.3 eV nm

k_F ~ 11 nm^{-1}

E_F ~ 9 eV

λ_{sd} ~ 8 nm spin diffusion length

l_m ~ 5 nm mean free path

$\eta = (\alpha_R k_F / E_F)^2$ of 0.1- 0.2 Rashba parameter

$\xi = (3/2)(\Gamma^0 / k_F^2)(\lambda_{sd}/l_m) \times \coth(t_N/\lambda_{sd})$ of 0.1 – 0.2 back-flow factor

increase in α due to SP

$$\alpha_{\parallel} \propto \frac{1+6\eta\xi}{1+\xi} + \frac{\eta}{2(1+\xi)^2}$$

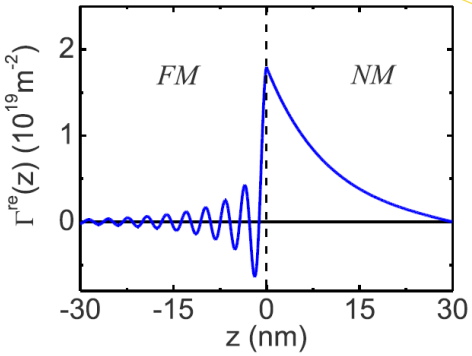
Chen, Zhang PRL 114 (2015)

SP in the presence of SO coupling

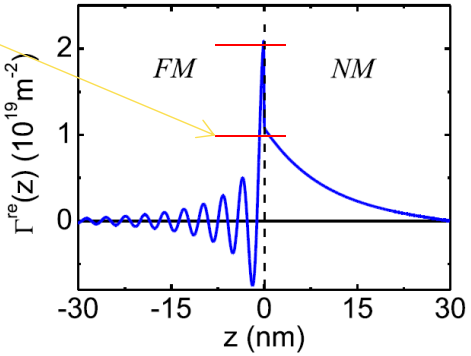
Theory:

- spin-pumping formalism in the presence of SOC
- origin of spin-memory loss at interfaces

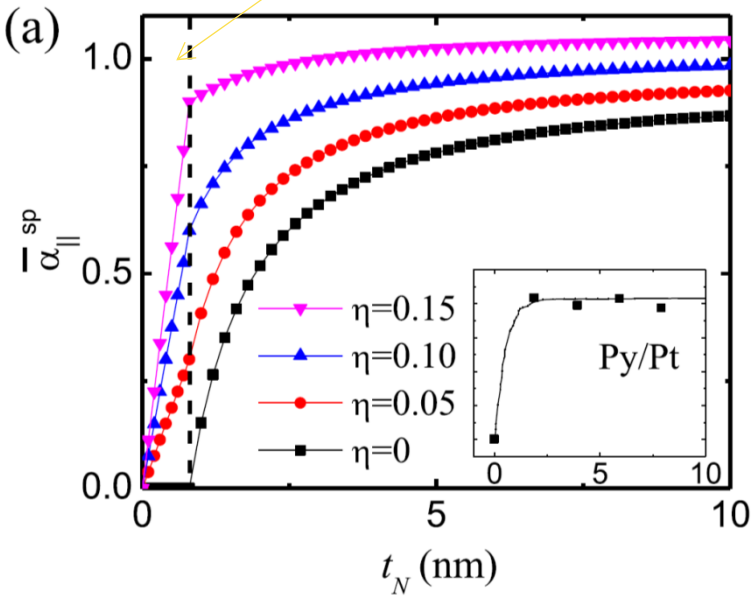
spin-memory loss
Or spin current jump



without SO



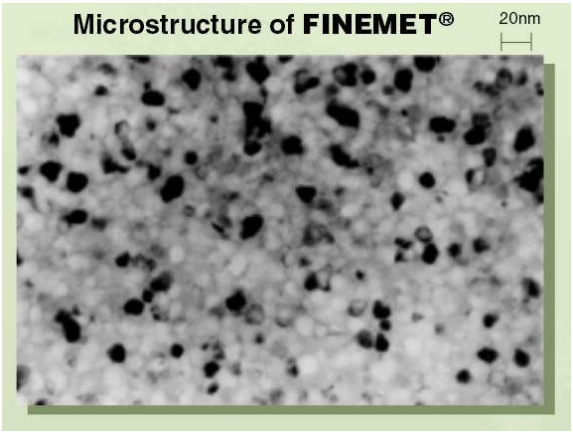
with SO



Chen, ZhangPRL 114 (2015)

Finemet

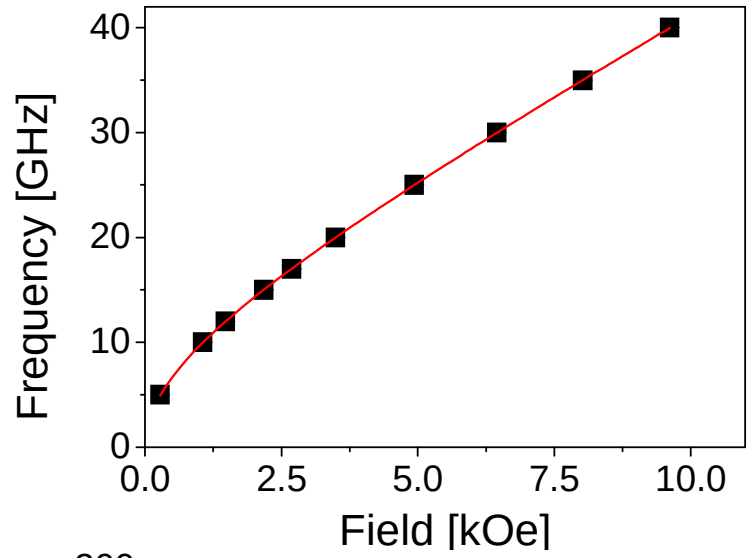
- Finemet ($Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$) with its nanocrystalline microstructure provides:
  - High permeability (~10^5)
  - High saturation magnetization (~ 1.2 T)
  - High squareness
  - Low magnetostriction (~10^{-6})



Y. Yoshizawa, S. Oguma, K. Yamauchi, J. Appl. Phys. 64 (10) (1988) 6044

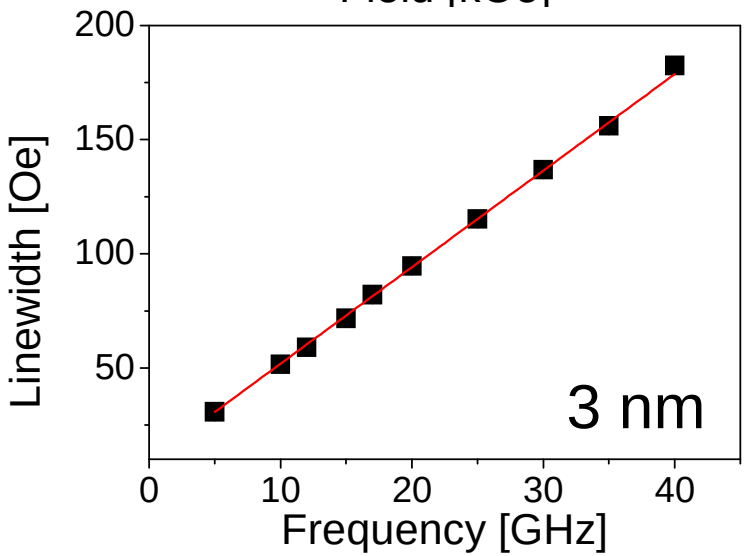
Nanocrystalline soft magnetic material Finemet, Hitachi Metals, Ltd.

VNA-FMR measurements of Al substituted Finemet



$$\left(\frac{\omega}{\gamma}\right)^2 = H_{FMR}\left(H_{FMR} + 4\pi M_{eff}\right)$$

$$4\pi M_{eff} = 4\pi M - 2K_{perp}/M$$

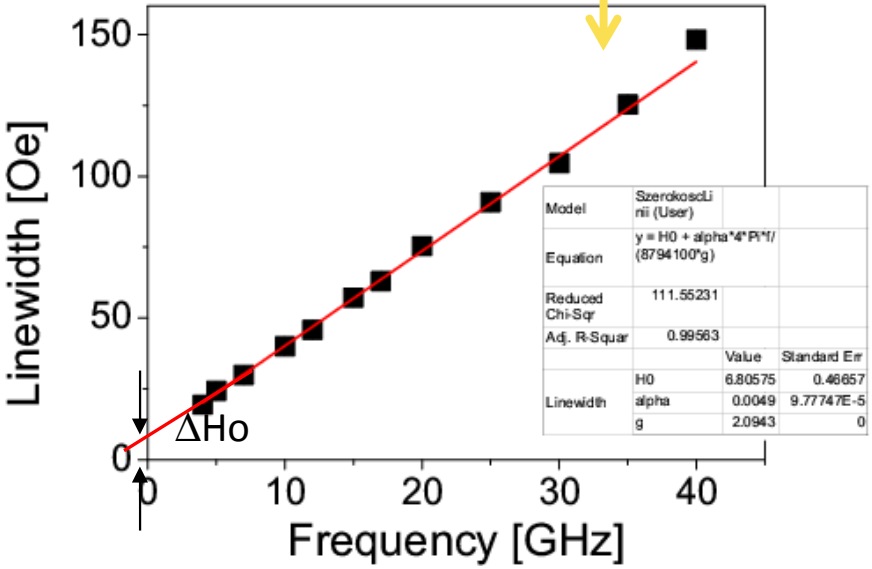


$$\Delta H = \frac{4\pi\alpha f}{|\gamma|} + \Delta H_0$$

Why Finemet+Al. ? ….
$Fe_{66.5}Cu_1Nb_3Si_{13.5}B_9Al_7$

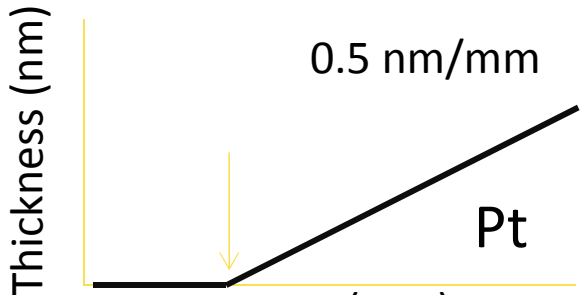
- Permalloy – widely used $\alpha = 8\times10^{-3}$ & $\Delta H_o = 10$ Oe
- CoFeB – low damping $\alpha = 4\times10^{-3}$ but $\Delta H_o = 10 - 20$ Oe
- **FINEMET + Al** * - $\alpha = 4\text{-}5\times10^{-3}$ & $\Delta H_o = 3 - 7$ Oe !
- **epi – YIG **** - $\alpha = 5\times10^{-4}$ & $\Delta H_o = 2 - 8$ Oe

$$\Delta H = \Delta H_0 + \frac{4\pi f \alpha}{\gamma}.$$



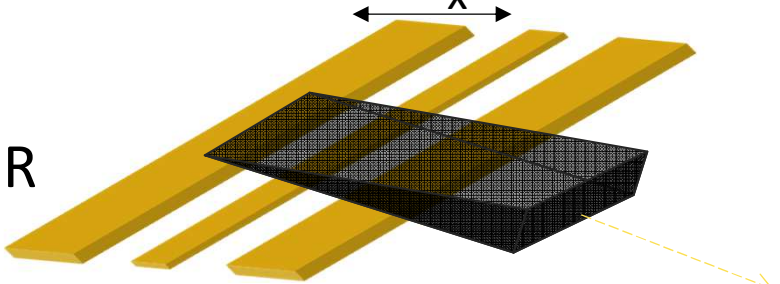
Essential issue for FM: damping as low as possible

VNA-FMR with CPW

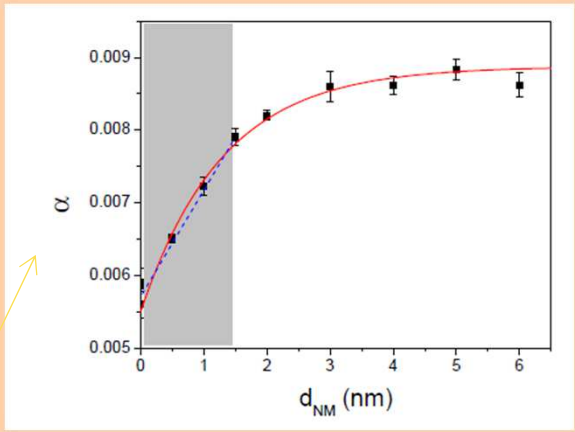


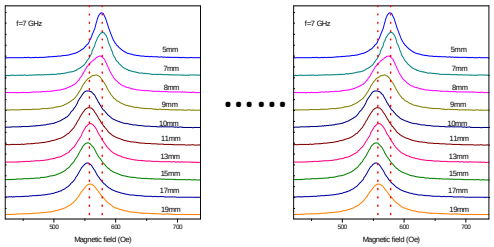
A Finemet thin film with wedged Pt capping layer

VNA-FMR



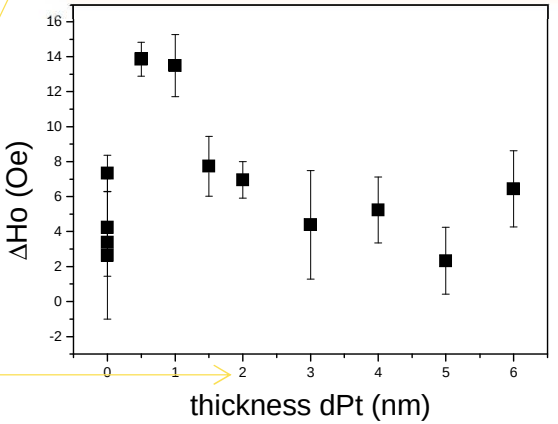
CPW



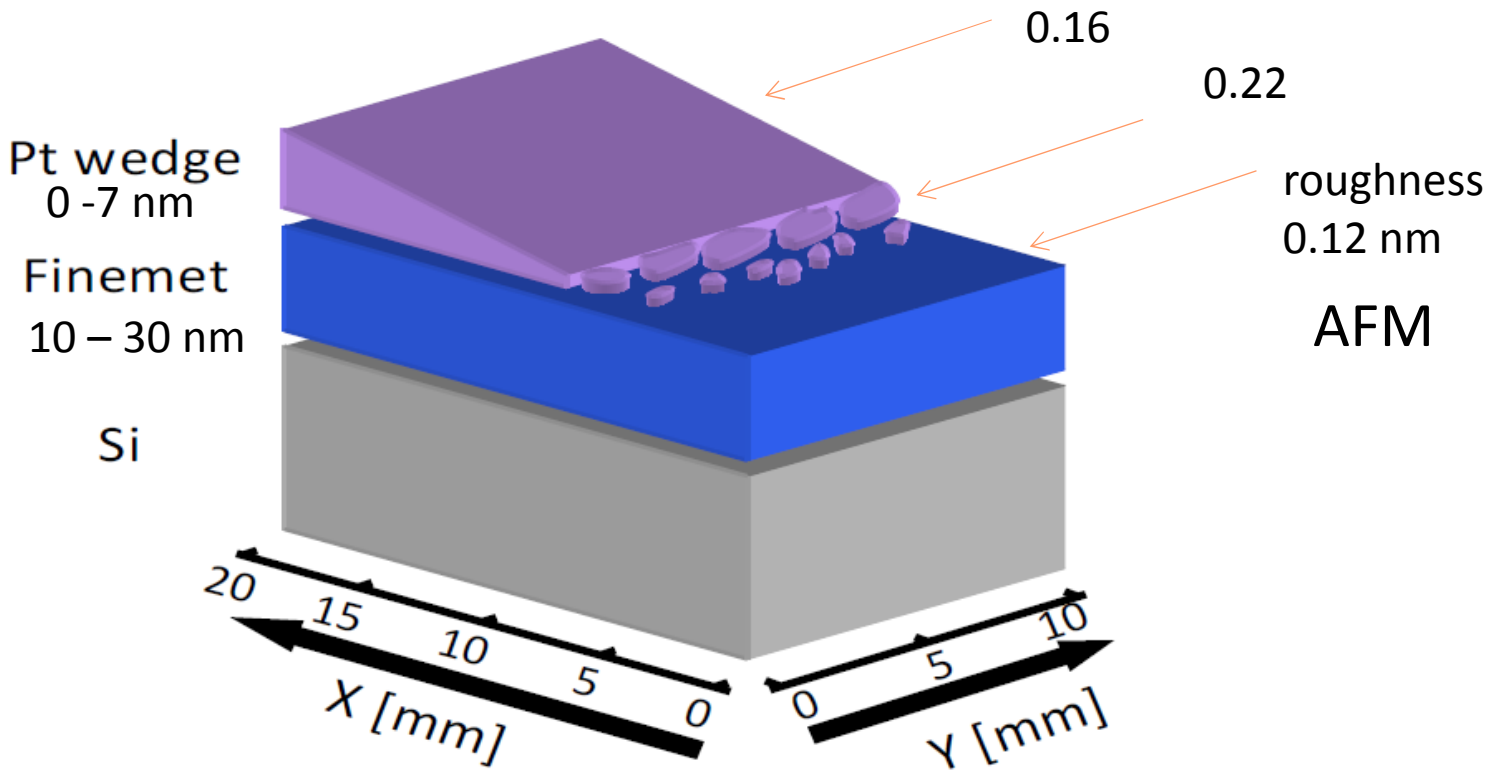


f: 3 -40 GHz

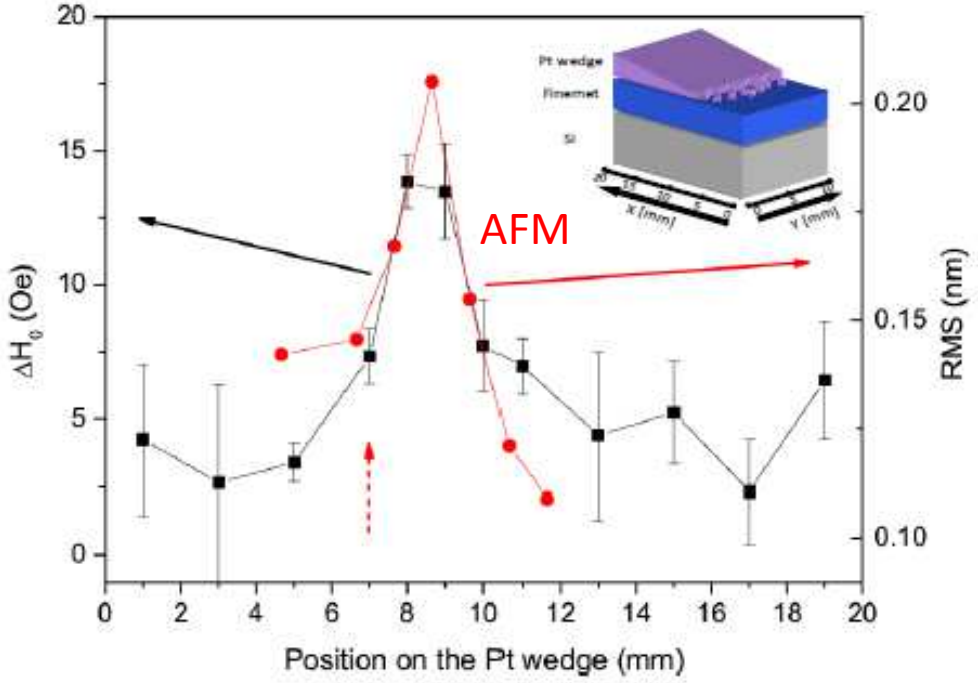
$$\Delta H = \Delta H_0 + \frac{4\pi f \alpha}{\gamma}$$



STRUCTURE of Finemet-Al with a Pt wedge

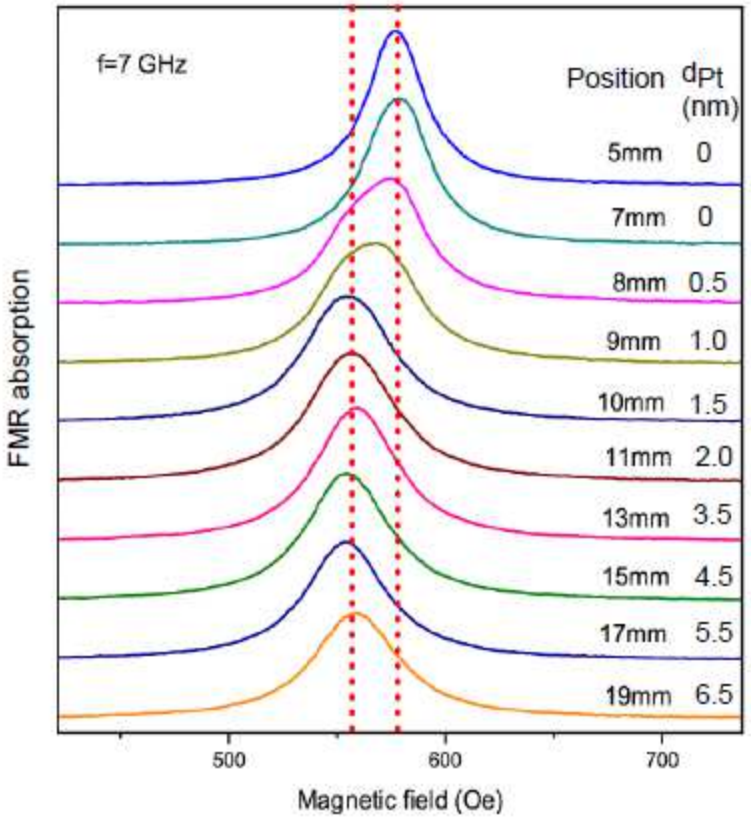


Finemet-Al with a Pt wedge



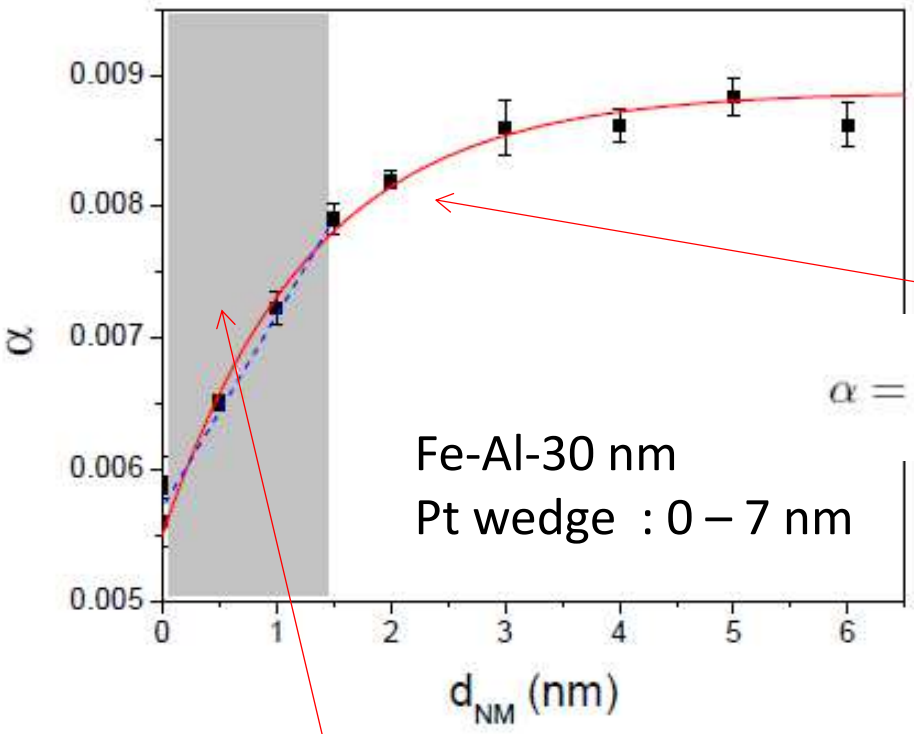
Low roughness with maximum for discontinuous Pt

Maximum in ΔH corresponds to maximum in RMS



Hr modulation

SPIN PUMPING in Finemet-Al capped with Pt



conventional theory

$$\alpha = \alpha_0 + \frac{g\mu_B}{4\pi M_S}\frac{g_{eff}^{\uparrow\downarrow}}{d_{Al-F}}\left(1-\exp\left(-\frac{2d_{Pt}}{\lambda_{sf}}\right)\right)$$

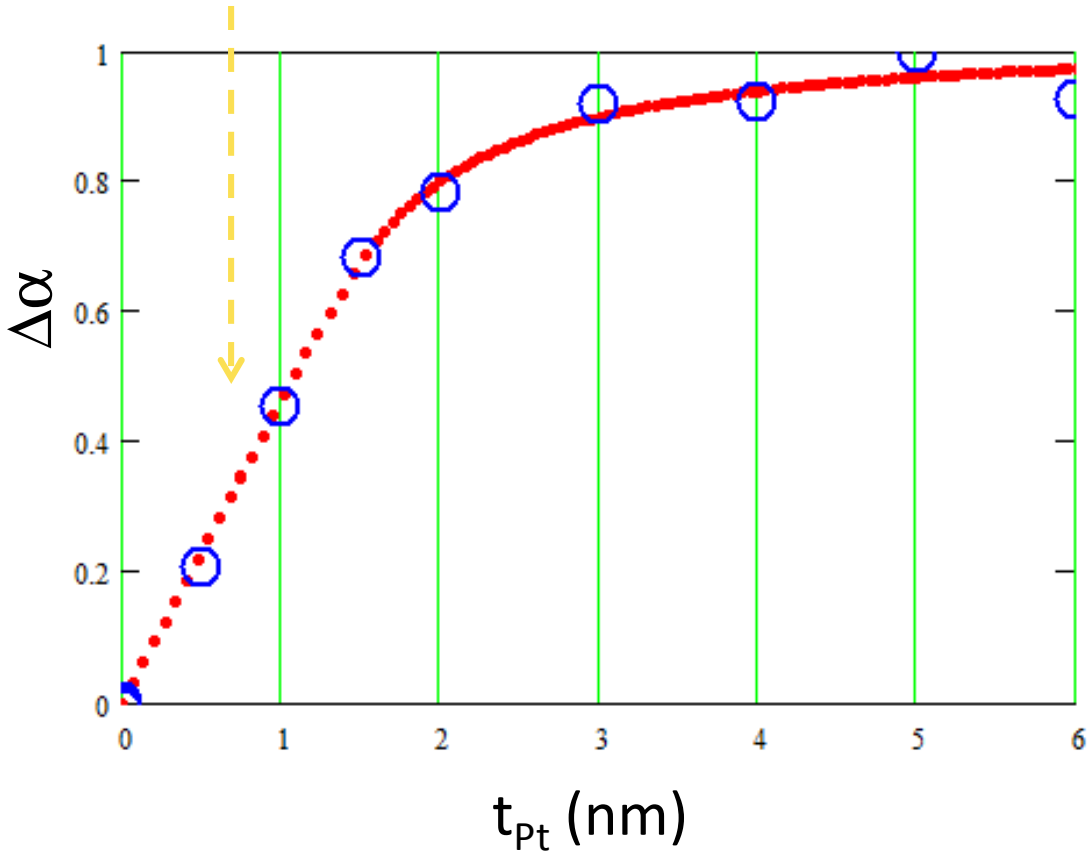
OK, but
this region
is ill defined

$g_{eff} = 5\times10^{15}$ cm^{-2}

$\lambda_{sf} = 2.5$ nm

CALCULATIONS of Δα within the framework of SOC

Pt islands 1 – 3ML thick



Γo ~ 7 nm^{-2}

α_R ~ 0.03 – 0.3 eV nm

k_F ~ 11 nm^{-1}

E_F ~ 9 eV

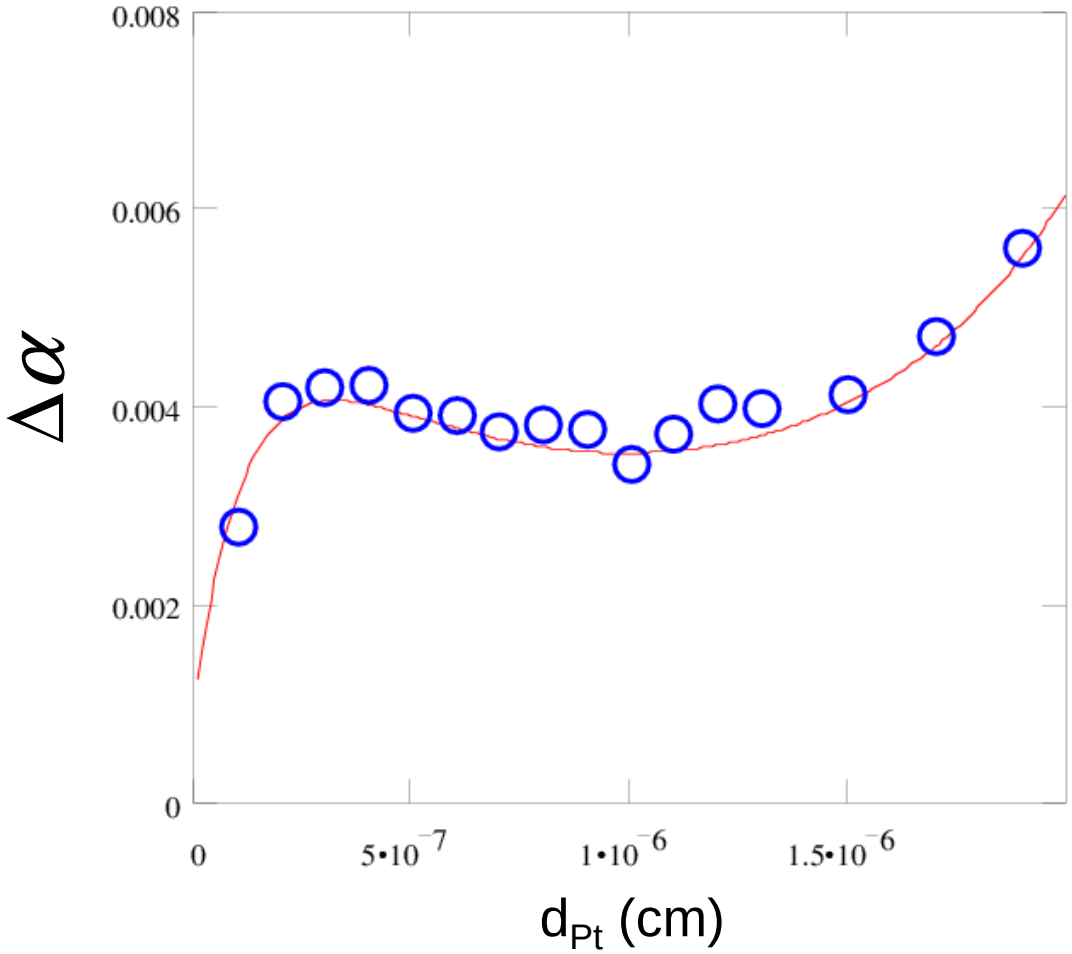
η ~ 0.1 – 0.2

ξ ~ 0.1 – 0.2

λsd ~ 8 nm spin diff. length

λm ~ 5 nm mean free path

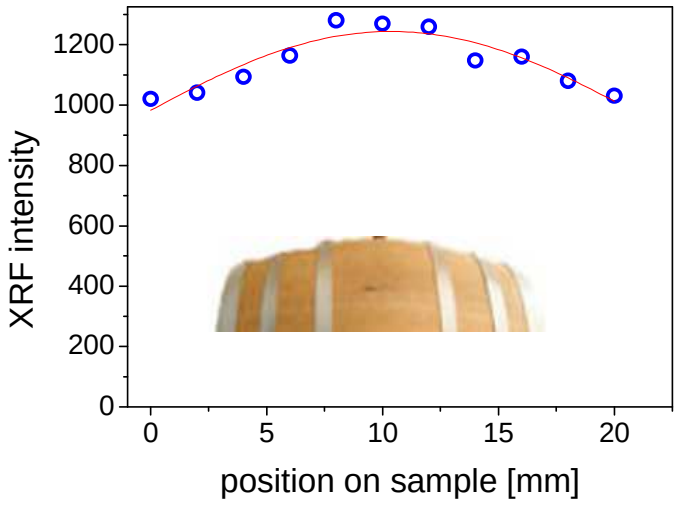
After ion beam etching



$$g^{\uparrow\downarrow}_{\text{eff}} = 1.7\times10^{15}\ \text{cm}^{-2}$$

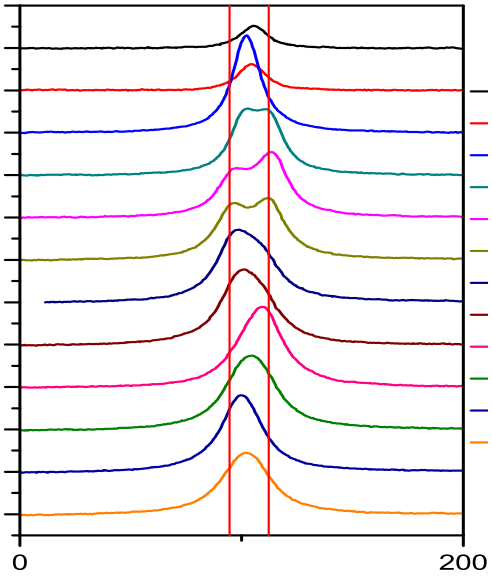
$$l_{\text{sf}} = 3\ \text{nm}$$

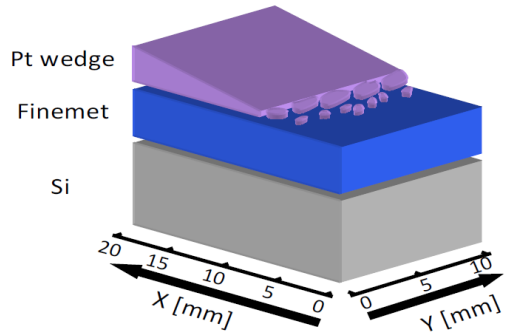
$$\Delta\alpha = g\mu_B \frac{g^{\uparrow\downarrow}_{eff}}{4\pi M_s t_{Al-F}} (1 - e^{\frac{-2t_{Pt}}{l_{sf}}})$$



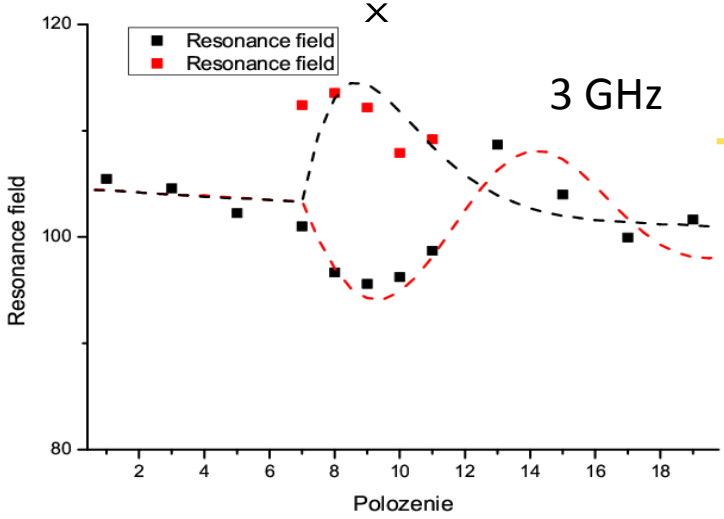
After ion etching sample's thickness is not homogenous

MODULATION of the resonance field (field-torque ?)



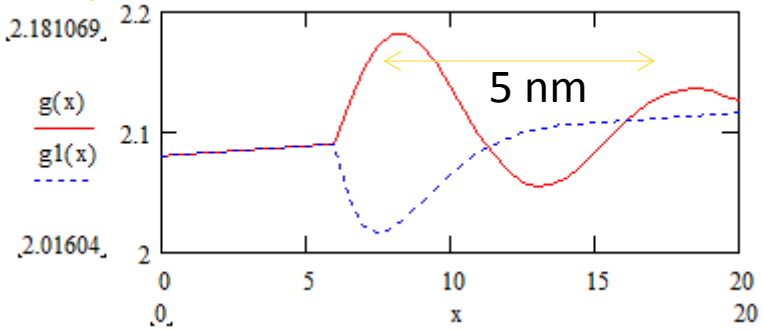


$$\mathbf{j}^s = \frac{\hbar}{4\pi}\left(g_r \mathbf{m} \times \frac{d\mathbf{m}}{dt} - g_i \frac{d\mathbf{m}}{dt}\right).$$

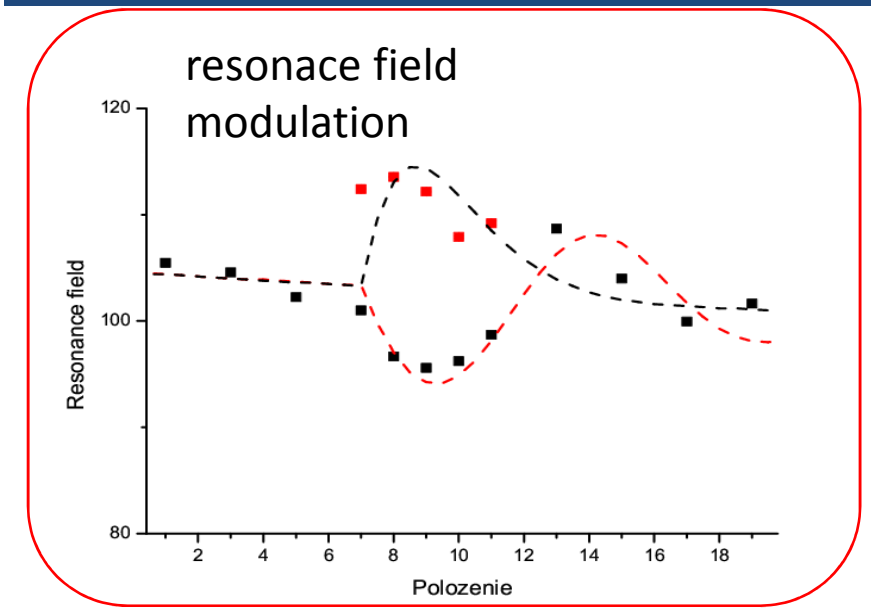


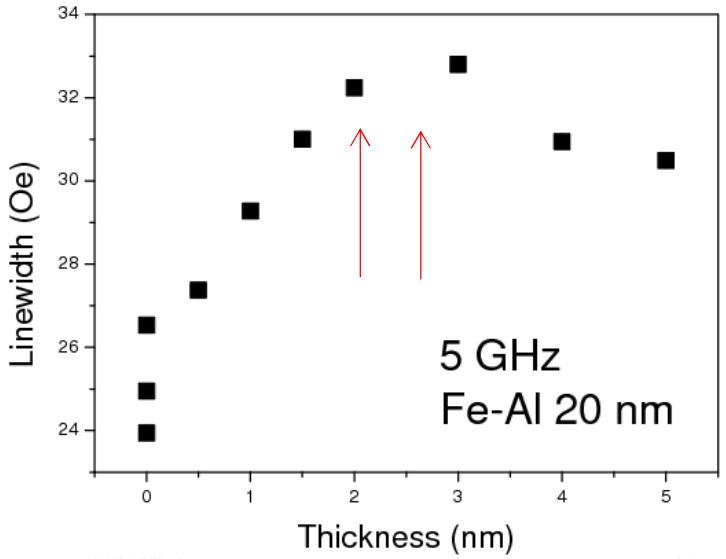
3 GHz

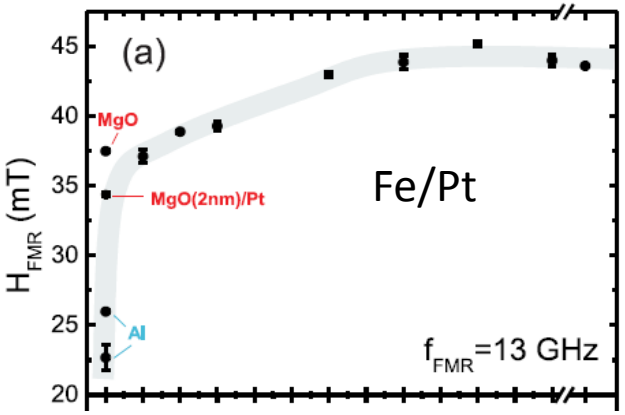
Disentangled with spectr. splitting **g** (t Pt) : 2 – 2.2 !

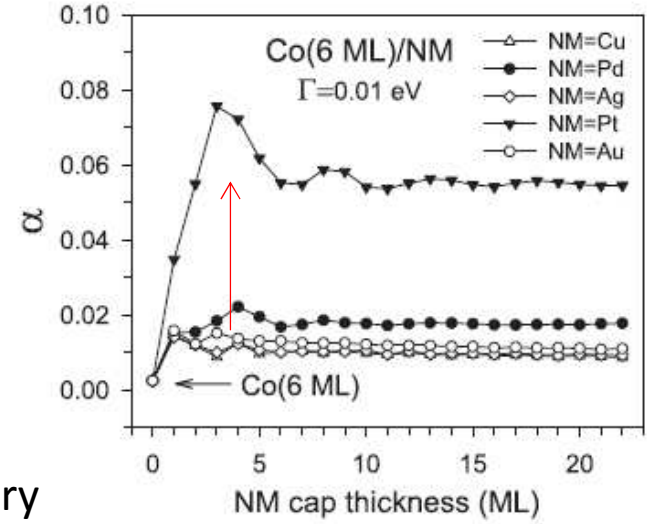


CHANGES in α and modulation of resonance field







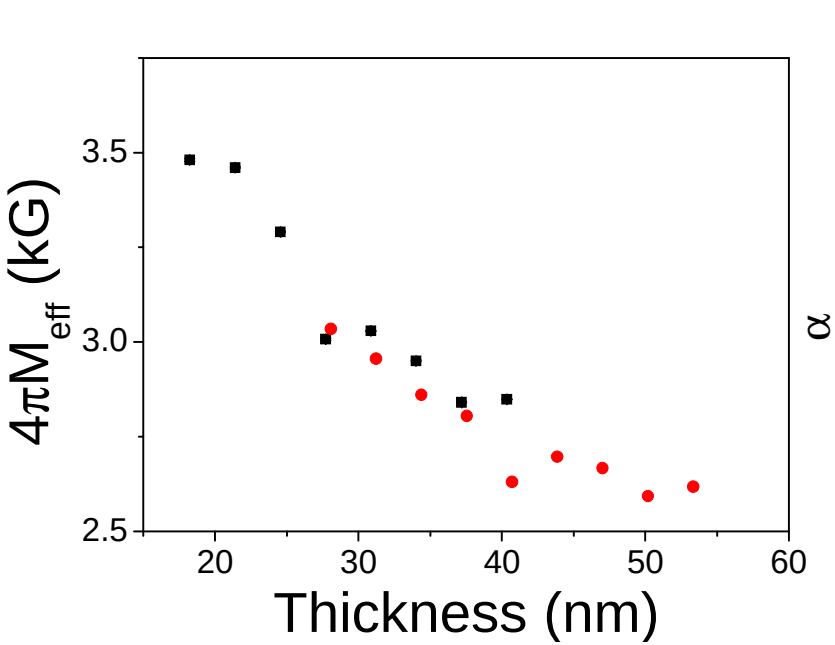


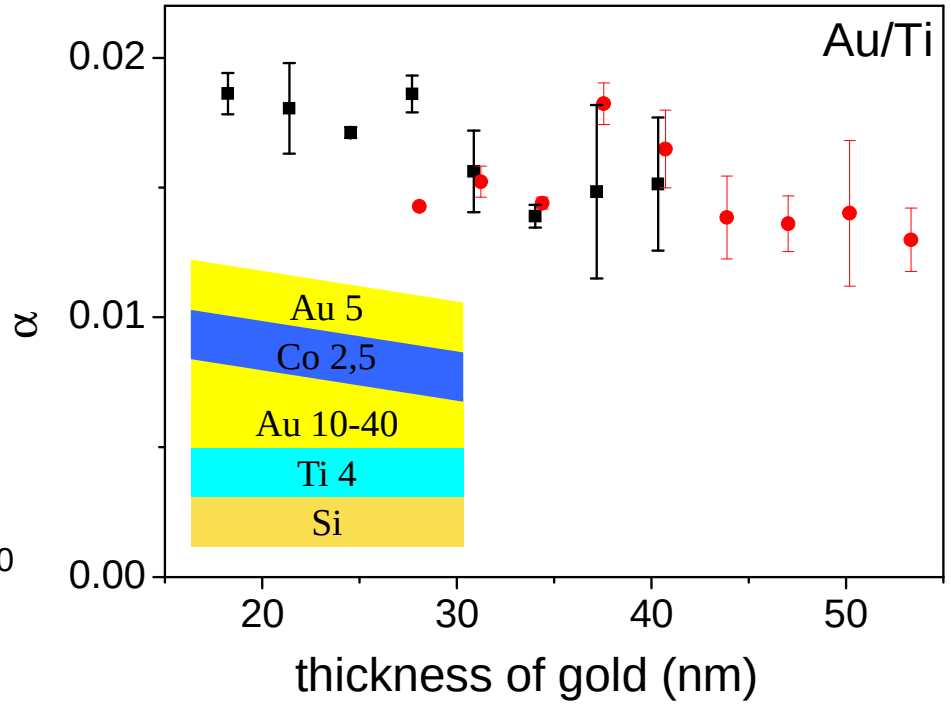
Theory

PHYSICAL REVIEW B **93**, 134405 (2016)

PHYSICAL REVIEW B **90**, 014420 (2014)

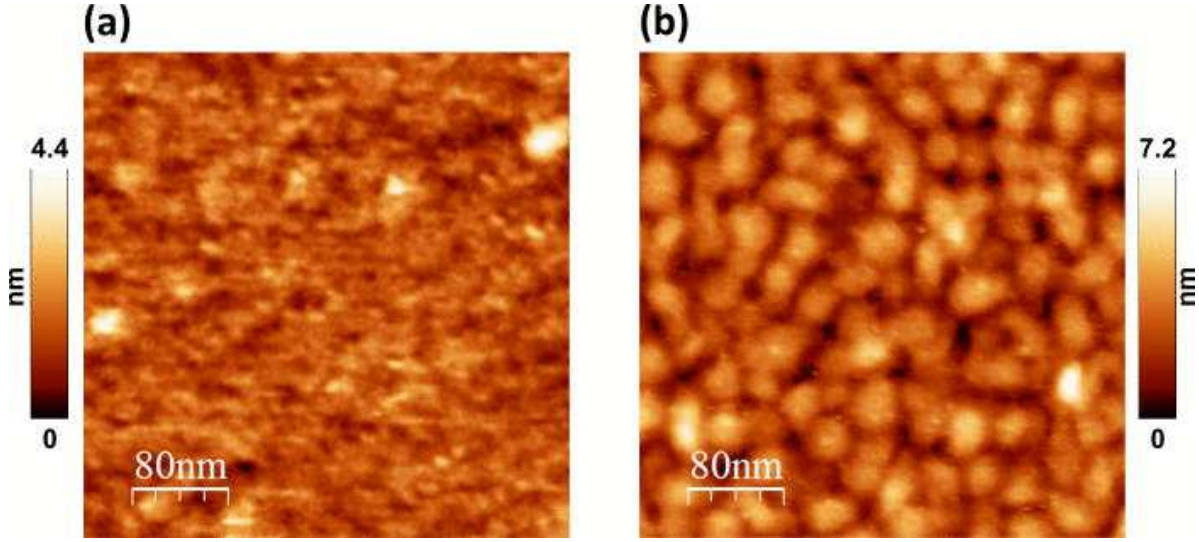
Gold buffer

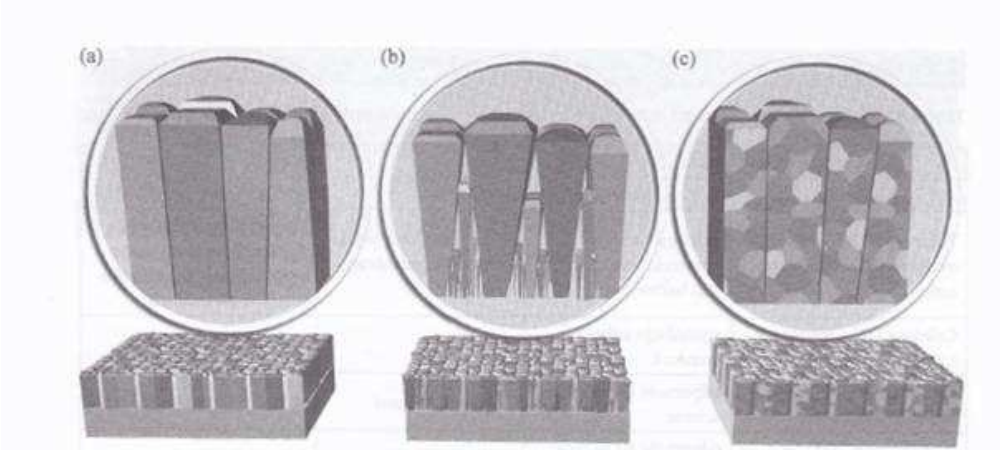




Untypical decrease of damping with thickness increase of gold

Surface roughness

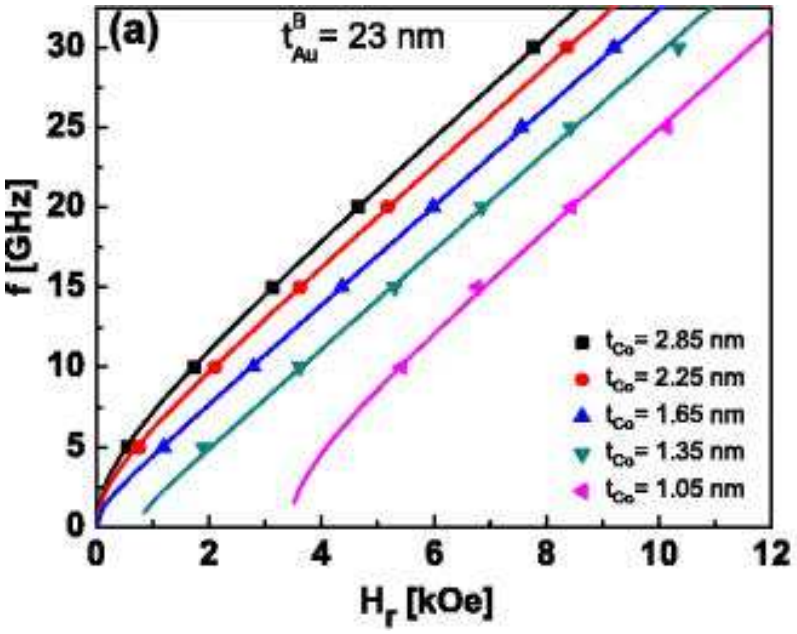


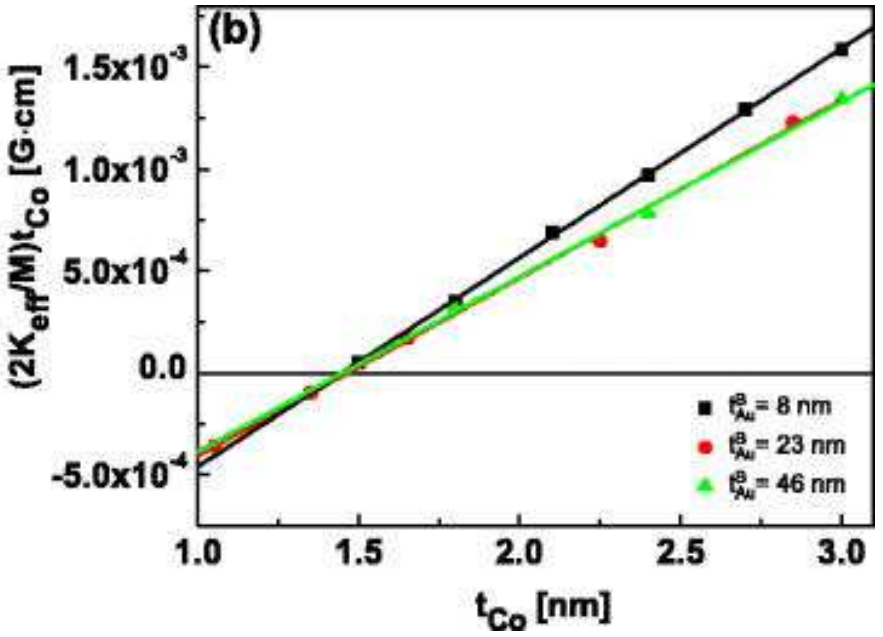


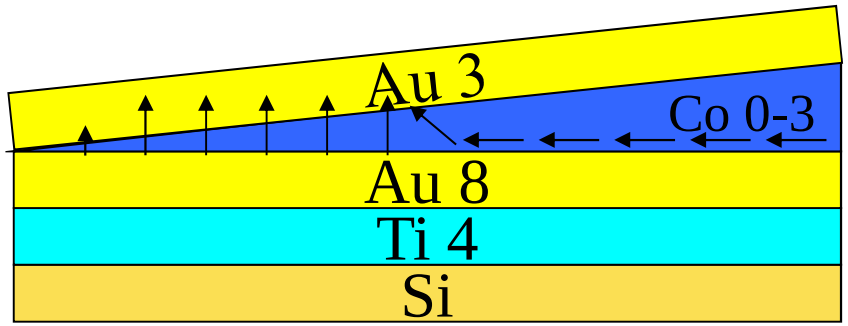
K. Kurzydłowski i M. Lewandowska "Nanomateriały inżynierskie konstrukcyjne i funkcjonalne"

Matczak et al., J. Appl. Phys. 114, 093911 (2013);

Surface roughness





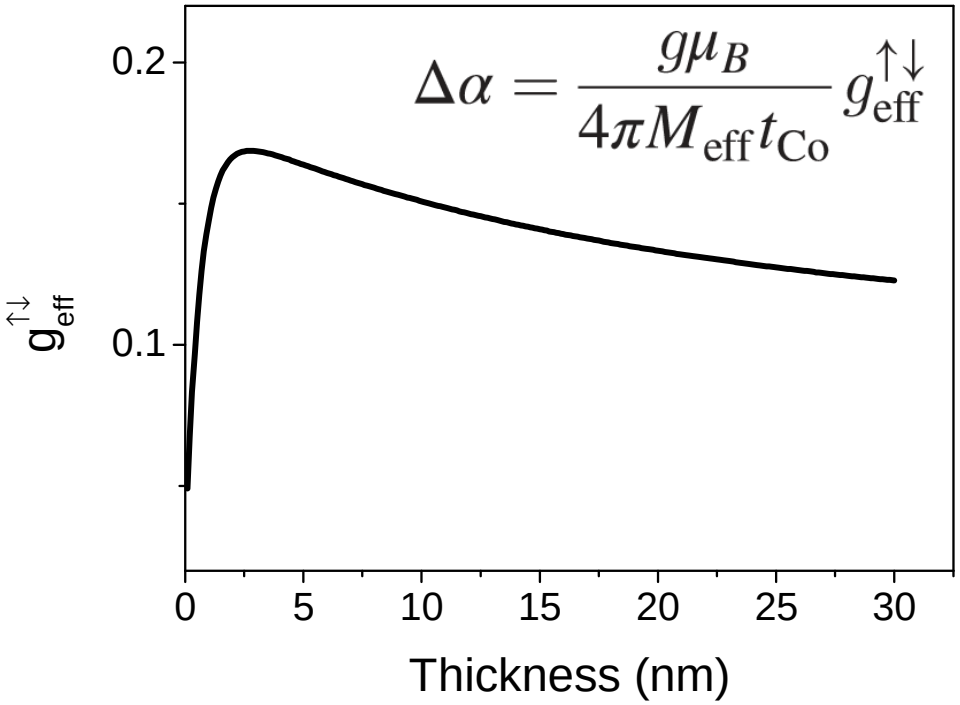


$$K_{pr} = \frac{K_s}{d} + K_V$$

Matczak et al., J. Appl. Phys. 114, 093911 (2013);

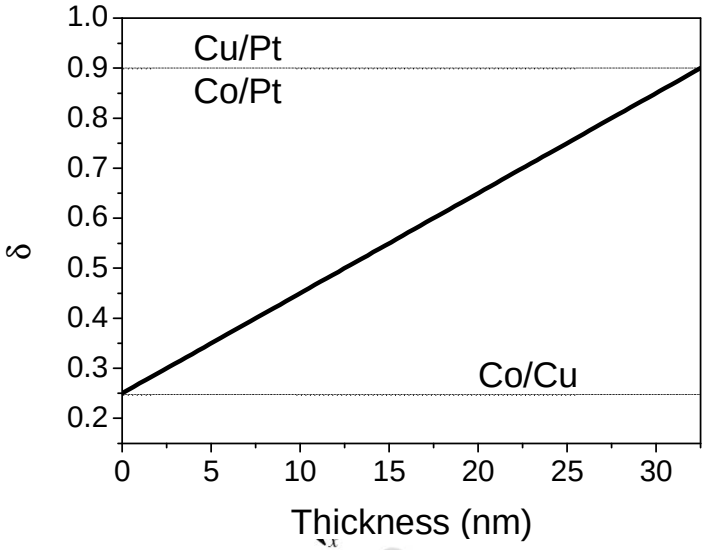
Simulation

$$\delta = t_{\mathrm{I}} / \ell^{\mathrm{I}}_{\mathrm{sf}}$$

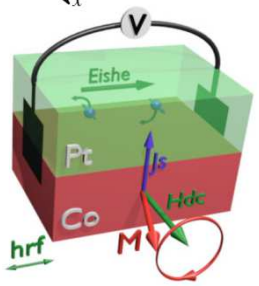


Depolarization probability

$[1 - \exp(-\delta)]$ 22% do 60%

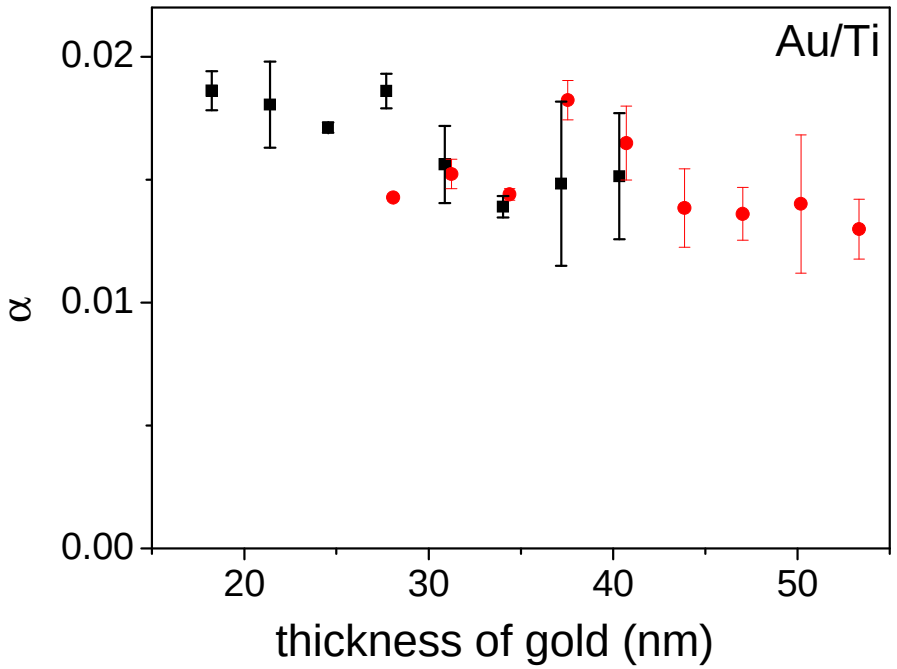


$$g^{\uparrow\downarrow}_{\mathrm{eff}} = g^{\uparrow\downarrow} \frac{r_{\mathrm{sI}} \cosh(\delta) + r^{\infty}_{\mathrm{sN}} \coth(\frac{t_N}{\ell^N_{\mathrm{sf}}}) \sinh(\delta)}{r_{\mathrm{sI}}[1 + \frac{1}{2}\sqrt{\frac{3}{\varepsilon}}\coth(\frac{t_N}{\ell^N_{\mathrm{sf}}})] \cosh(\delta) + [r^{\infty}_{\mathrm{sN}} \coth(\frac{t_N}{\ell^N_{\mathrm{sf}}}) + \frac{1}{2}\frac{{r_{\mathrm{sI}}}^2}{r^{\infty}_{\mathrm{sN}}}\sqrt{\frac{3}{\varepsilon}}] \sinh(\delta)}$$

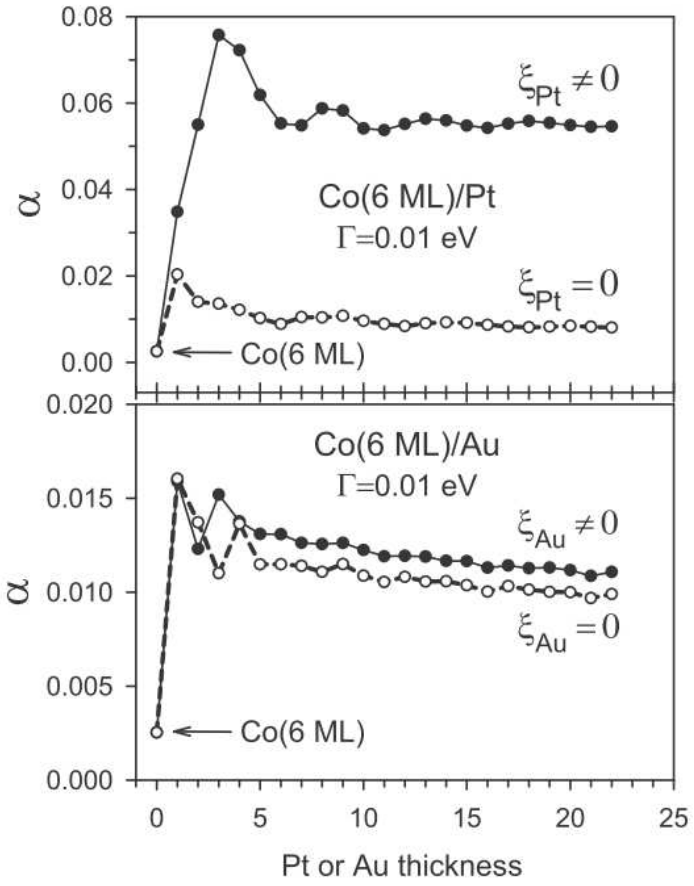


J.-C. Rojas-Sánchez et al., PRL **112**, 106602 (2014)

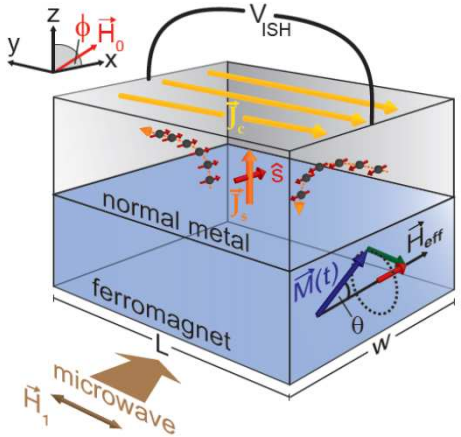
Nonlocal damping mechanism



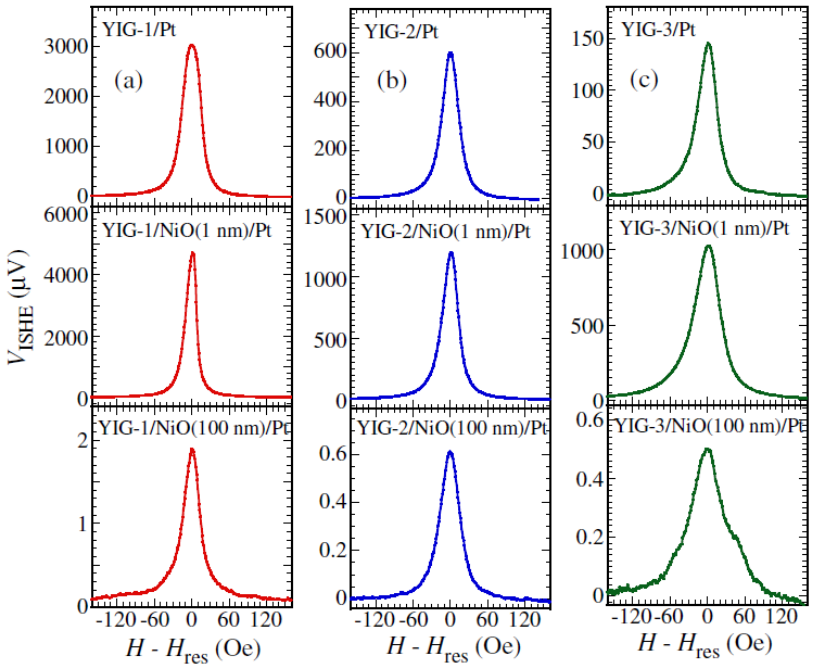
PHYSICAL REVIEW B **90**, 014420 (2014)

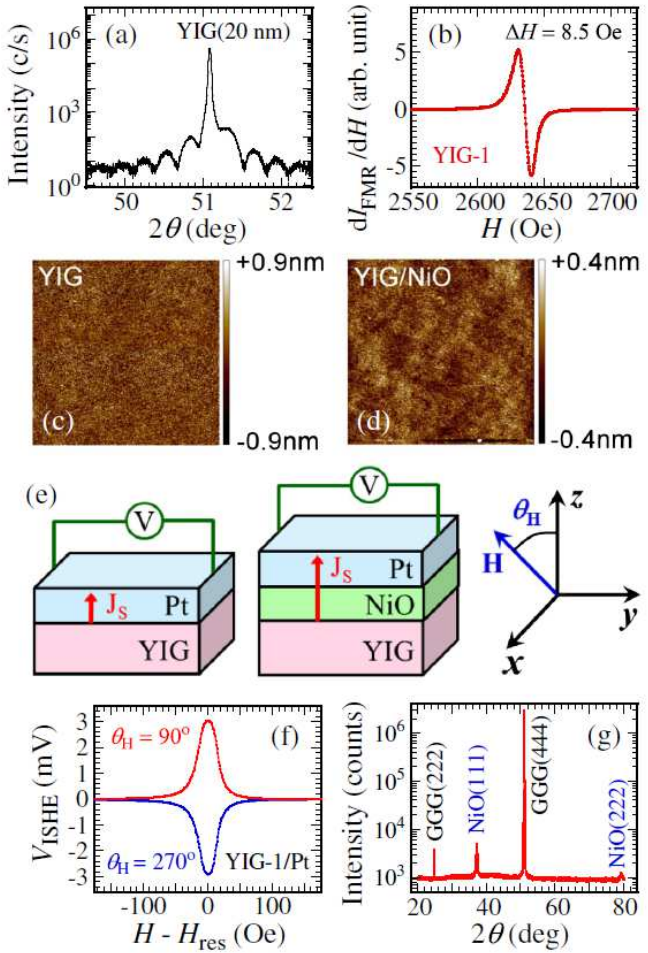


ISHE measurements



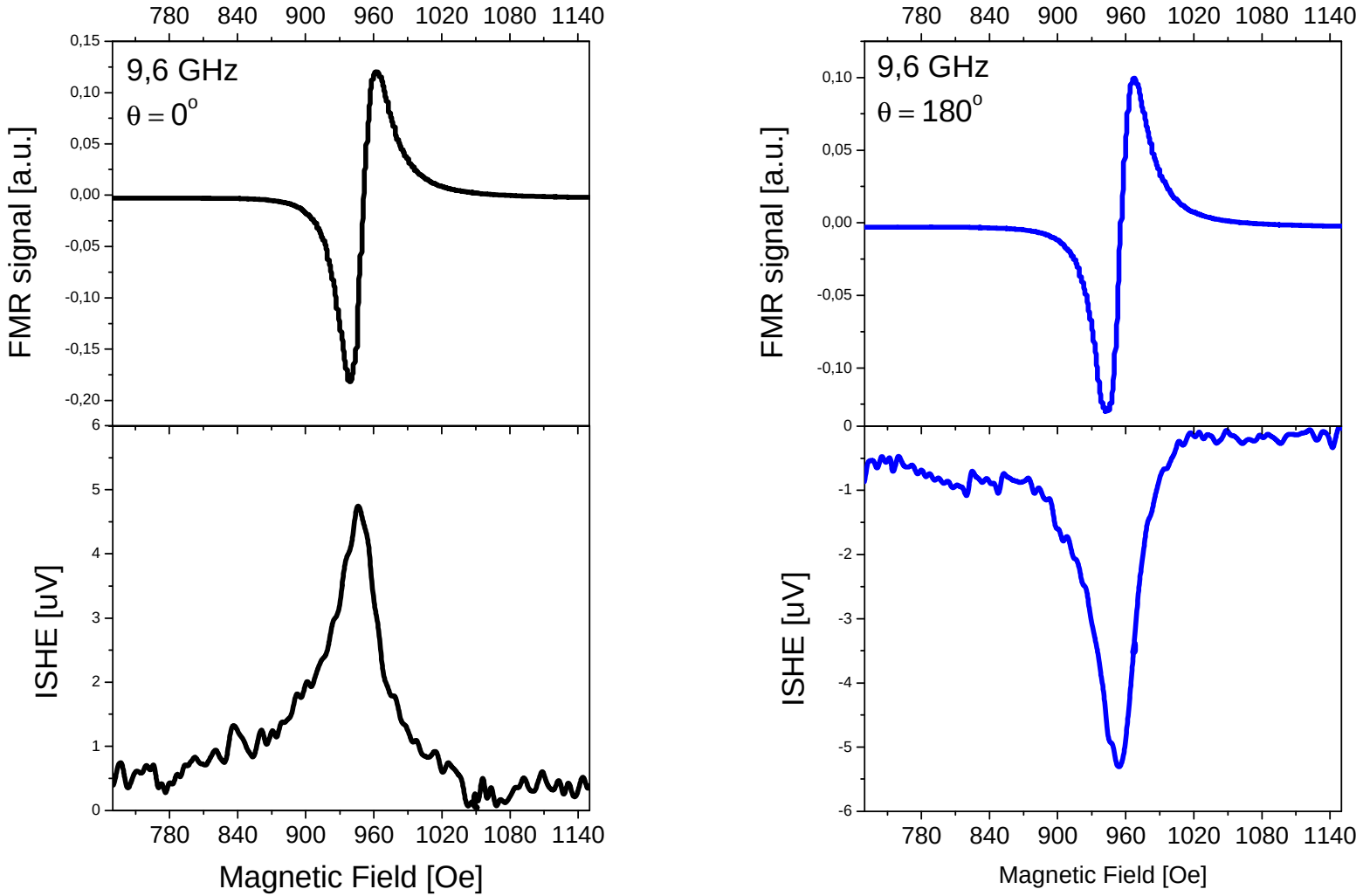
Spin current through NiO barrier





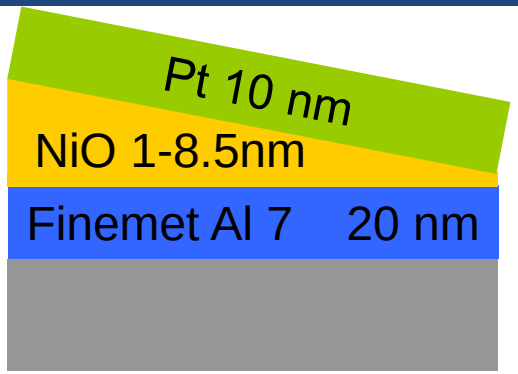
PRL **113,** 097202 (2014)

ISHE measurements

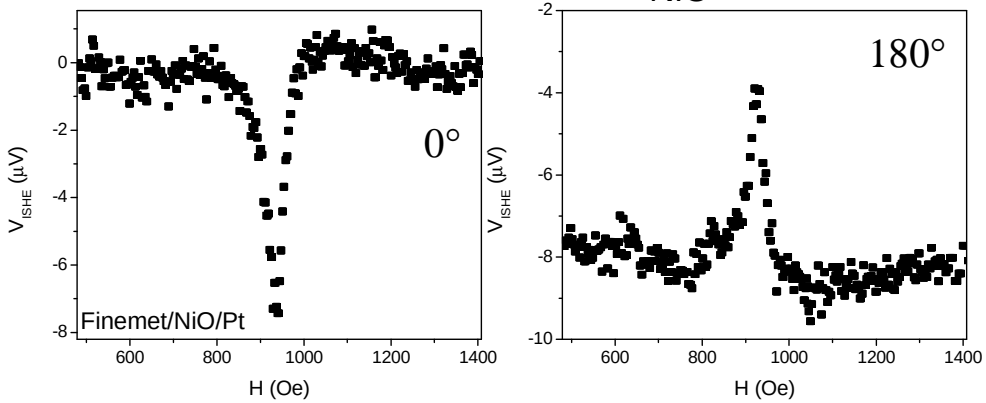


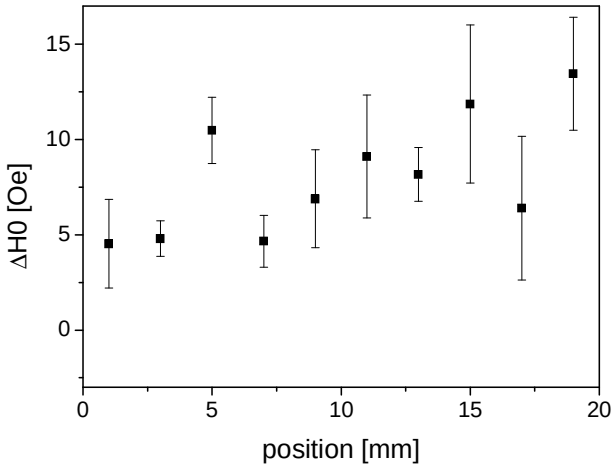
Finemet 18nm / NiO 10nm / Pt 10nm

Spin pumping measurements

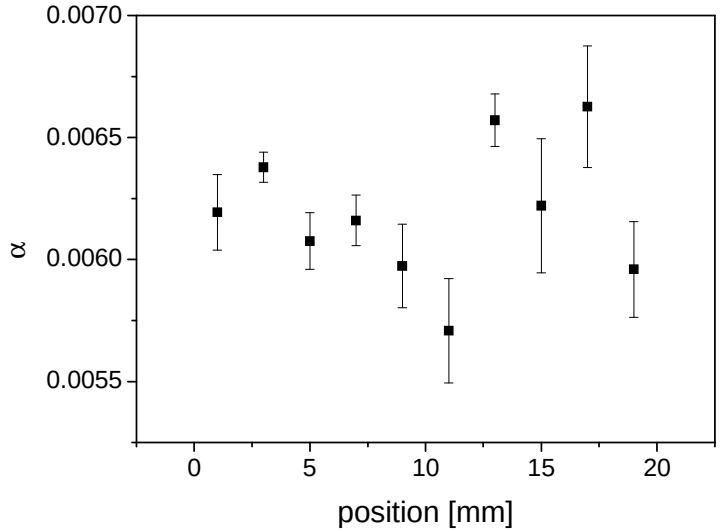


t_{NiO}= 4 nm



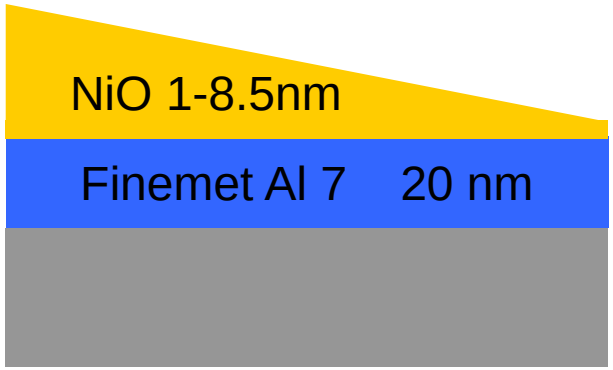


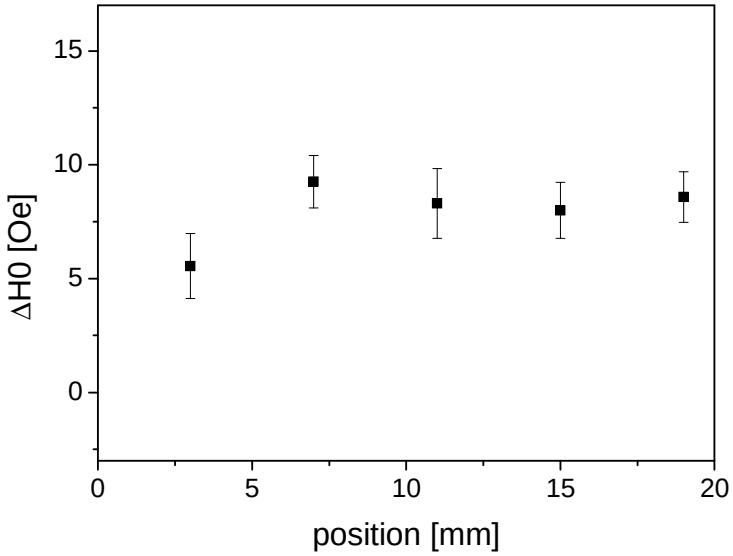
ISHE observation

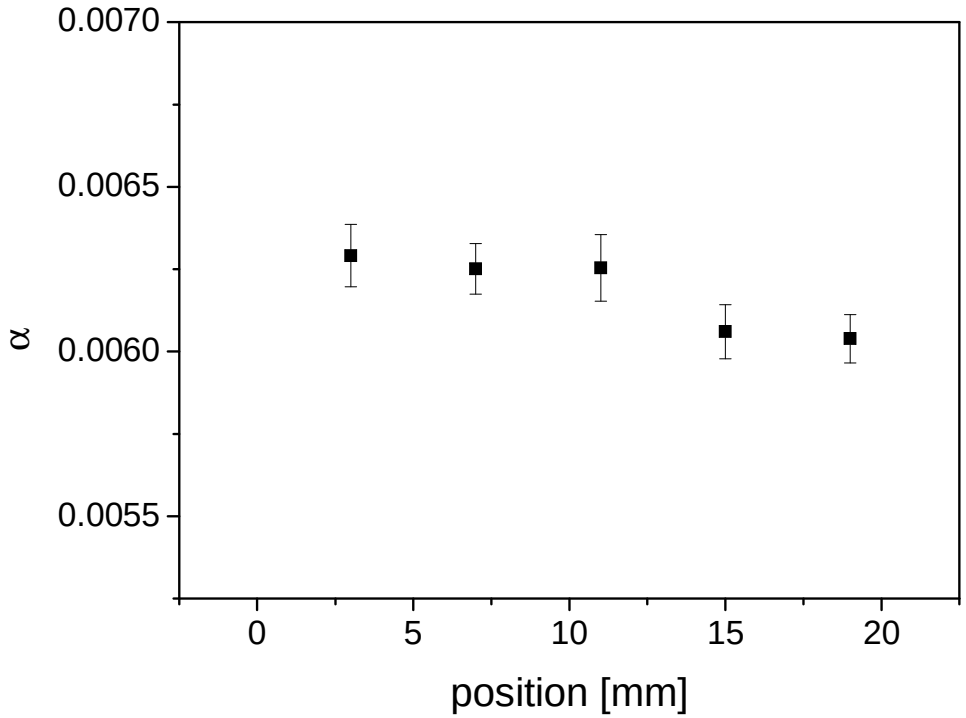


Slight enhancement of damping

Damping measurements

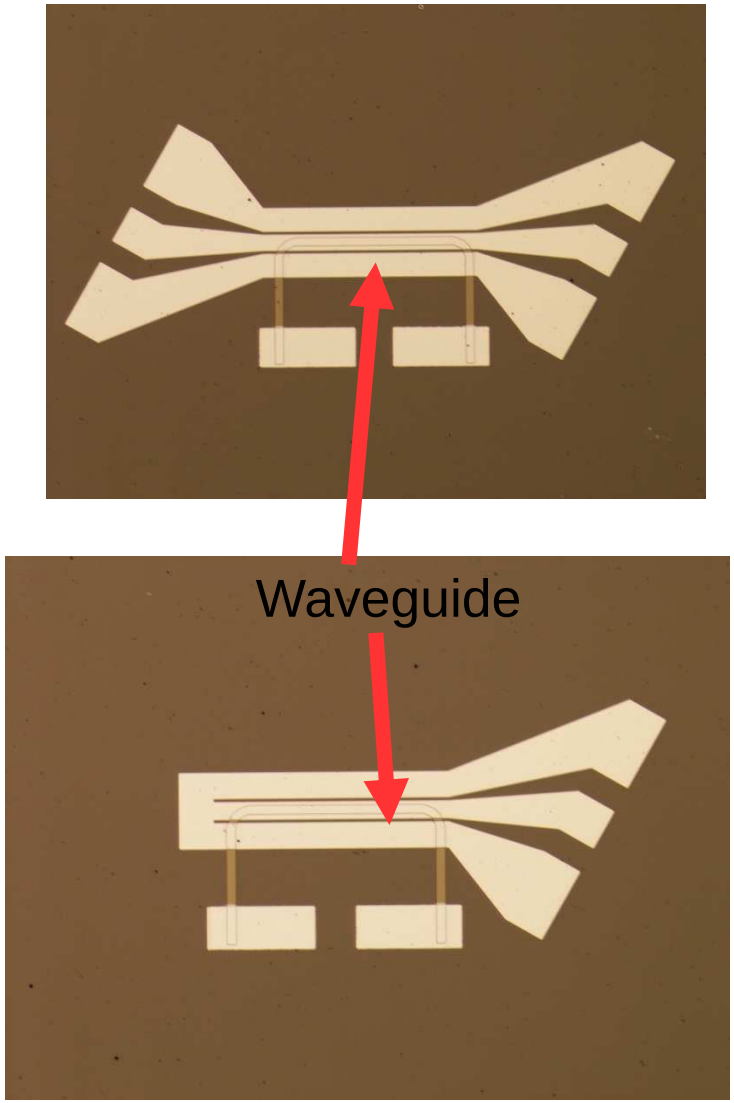


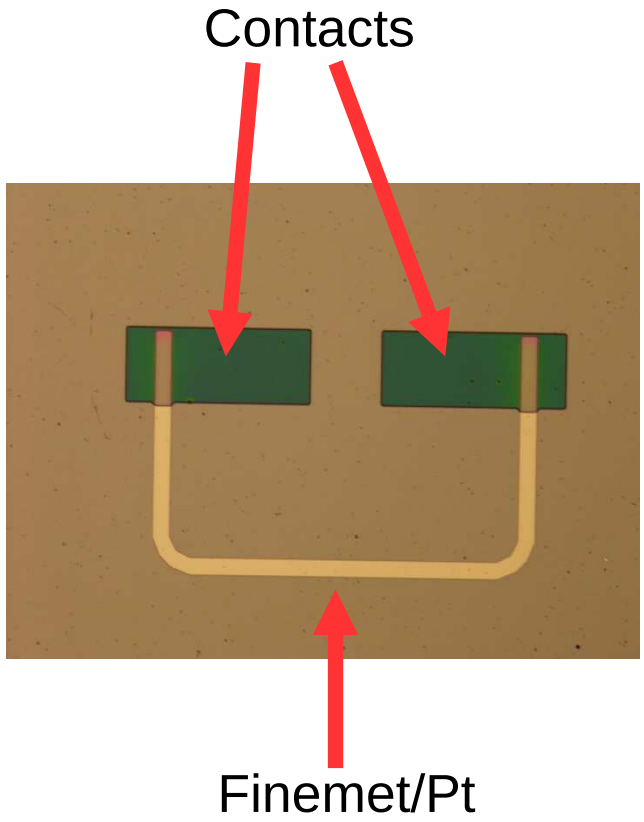




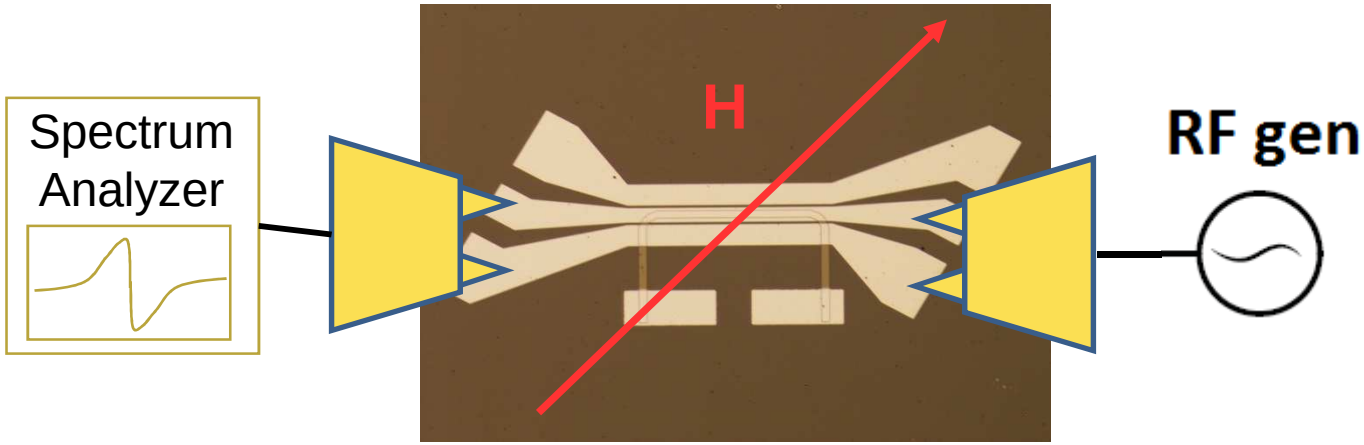
Slight enhancement of damping

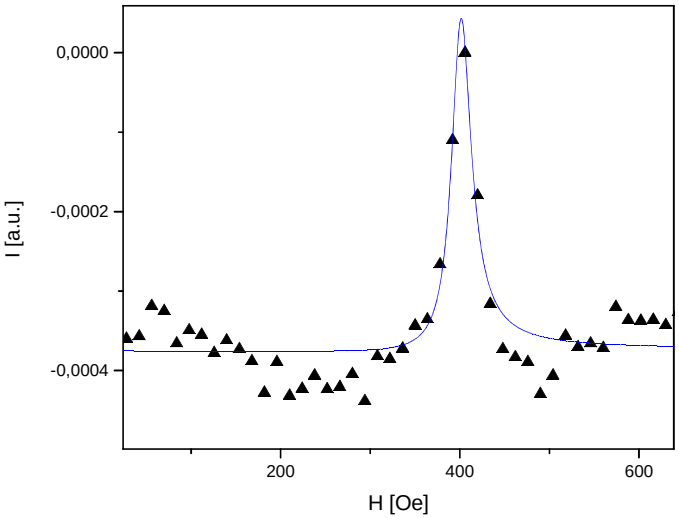
Litography

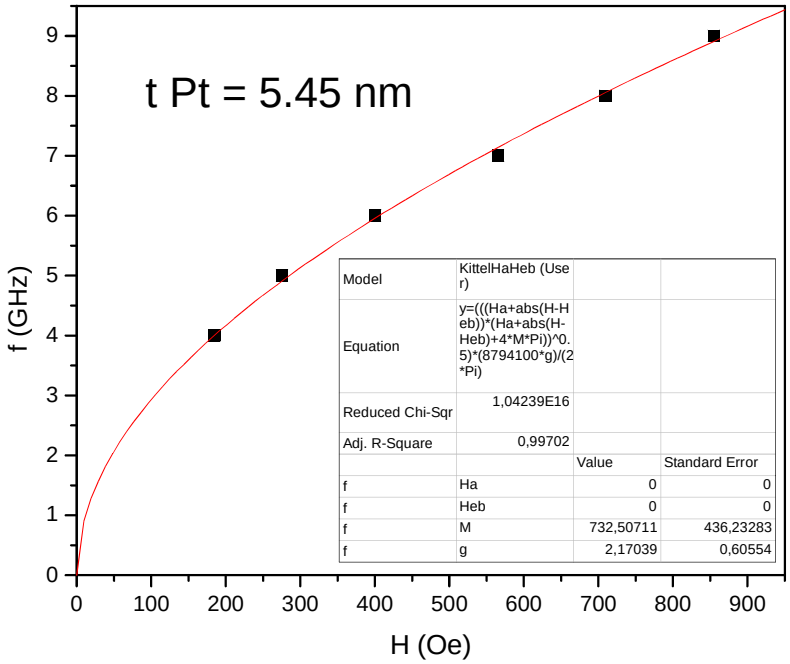




SNA-FMR


Spectrum Analyzer
H
RF gen


0,0000
-0,0002
-0,0004
I [a.u.]
200
400
600
H [Oe]

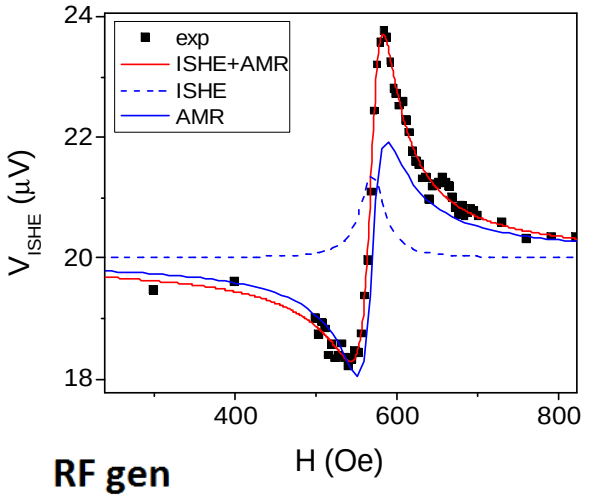

t Pt = 5.45 nm
f (GHz)
H (Oe)
0
100
200
300
400
500
600
700
800
900
1
2
3
4
5
6
7
8
9
Model KittelHaHeb (User)
Equation y=(((Ha+abs(H-Heb))*(Ha+abs(H-Heb)+4*M*Pi))^0.5)*(8794100*g)/(2*Pi)
Reduced Chi-Sqr 1,04239E16
Adj. R-Square 0,99702
Value Standard Error
f Ha 0 0
f Heb 0 0
f M 732,50711 436,23283
f g 2,17039 0,60554

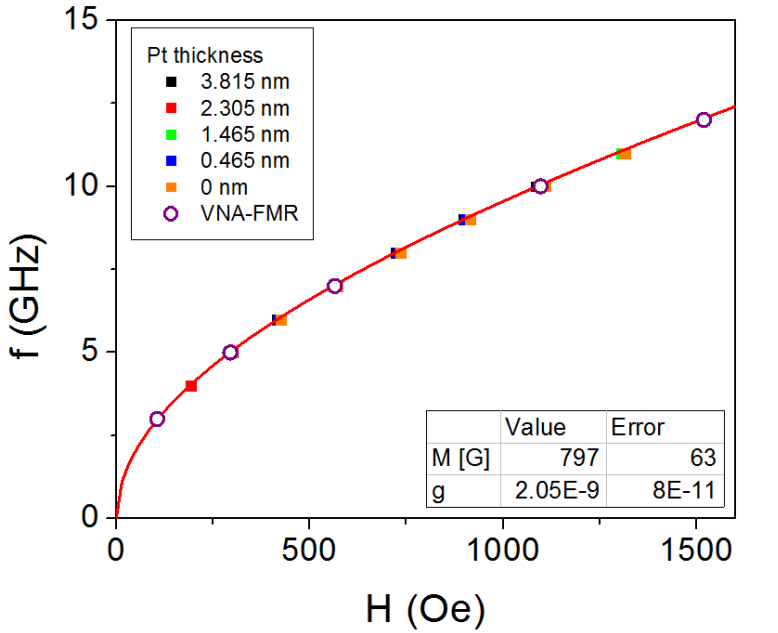
ISHE devices

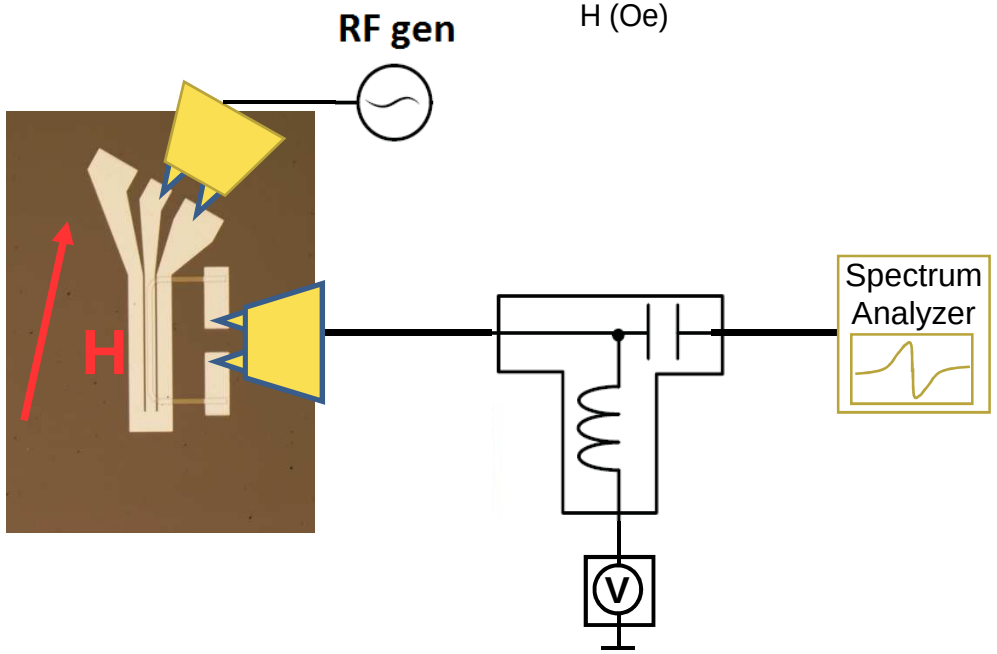
ISHE voltage measured on ISHE devices

Signal = AMR voltage + ISHE voltage

Signal = antisymetric + symetric



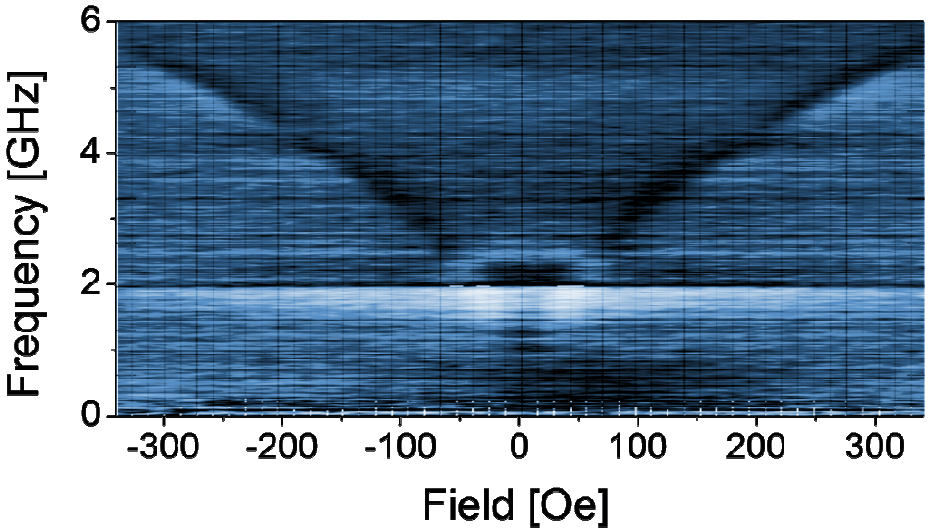




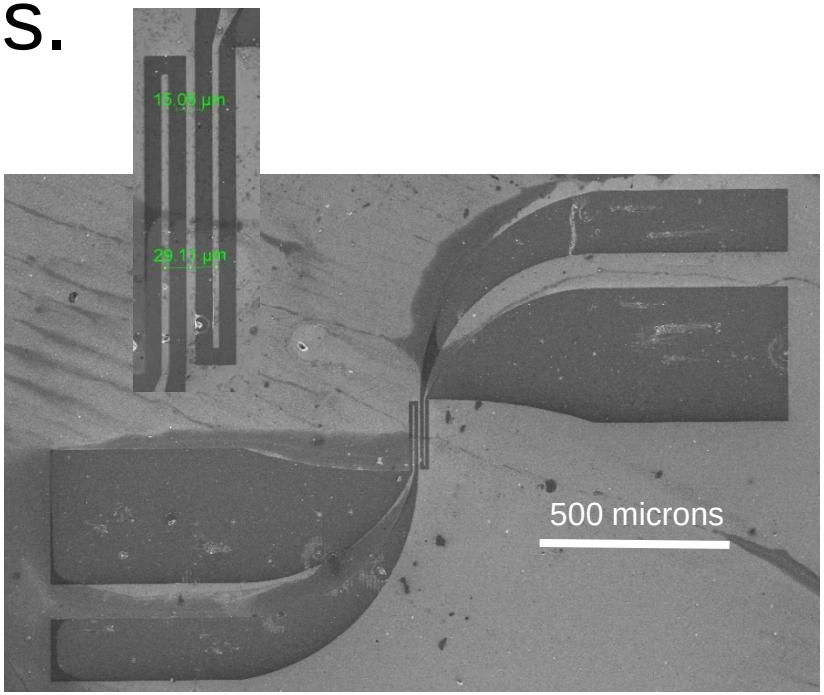
Propagation of magnons

- Magnon propagation in Al substituted Finemet is of 15 microns.

Measurement of S_{21}



VNA-FMR measurements



SUMMARY

- Interface is discontinuous – Pt islands up to **1.5** nm
- SP needs the presence of **SO** at interfaces
- Experiment – α **vs. d(Pt)** – can be described assuming reasonable values of parameters for Pt ($\mathbf{E_F}$, $\mathbf{k_f}$, λ_{sd}, λ_m ..)
- Modulation of **Hr** – to be explained
- Observation of spin current flow through NiO
- ISHE measurements in Finemet/Pt devices

Gościańska (Finemet, technology); H. Głowiński (experiment & analysis); A. Krysztofik (experiment); J. Barnas(theory); M. Cecot & T. Stobiecki (ISHE)

SWISS CONTRIBUTION

NANOSPIN

Thank you for your attention!

AGH

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

IF PAN

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